

(12) **United States Patent**
Haque et al.

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(54) **LOW VOLTAGE, LOW POWER MEMS TRANSDUCER WITH DIRECT INTERCONNECT CAPABILITY**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 611 days.

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Related U.S. Application Data

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H01L 41/08 (2006.01)
A61B 8/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **A61B 8/4494** (2013.01); **A61B 8/0883** (2013.01); **A61B 8/145** (2013.01);
(Continued)

(58) **Field of Classification Search**

CPC . H01L 41/098; H01L 41/0805; H01L 41/053;
G01S 7/52079; G01S 7/521;

(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,088,323 A 5/1963 Welkowitz et al.
4,156,800 A 5/1979 Sear et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP 3453056 A1 3/2019
WO WO-2013044471 A1 * 4/2013 G01N 29/24

(Continued)

OTHER PUBLICATIONS

PCT/US2017/063163 International Search Report and Written Opinion dated Feb. 15, 2018.

(Continued)

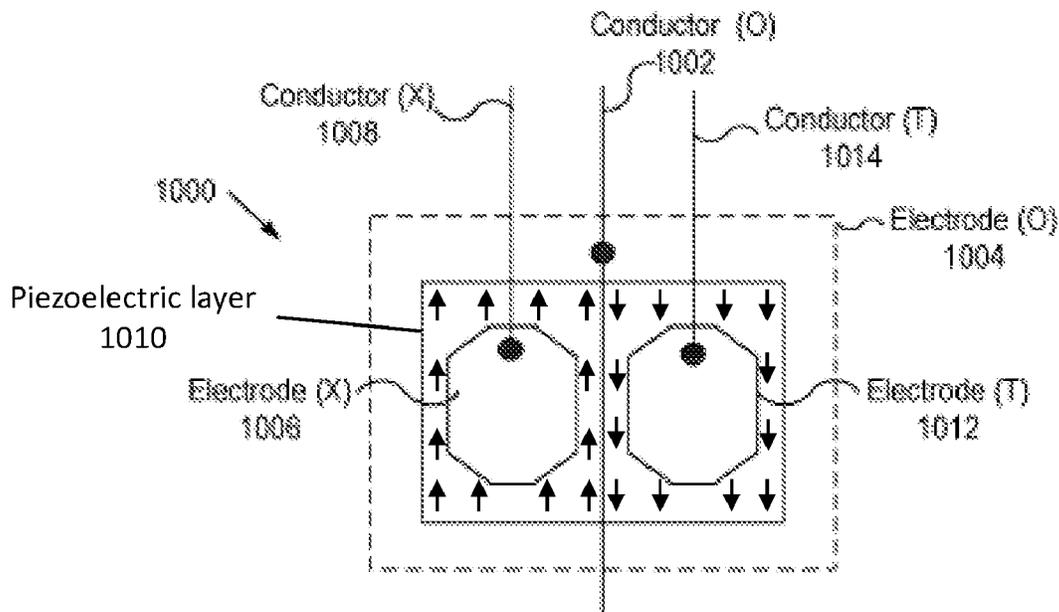
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(57) **ABSTRACT**

A transceiver includes an array of pMUT elements, where each pMUT element includes: a substrate; a membrane suspending from the substrate; a bottom electrode disposed on the membrane; a piezoelectric layer disposed on the bottom electrode; and a first electrode disposed on the piezoelectric layer. Each pMUT element exhibits one or more modes of vibration.

33 Claims, 36 Drawing Sheets



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G01S 7/52 (2006.01)
H01L 41/09 (2006.01)
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A61B 8/14 (2006.01)
B06B 1/02 (2006.01)
G01S 7/521 (2006.01)
G01S 15/89 (2006.01)
H01L 41/053 (2006.01)

(52) **U.S. Cl.**
CPC **A61B 8/4483** (2013.01); **A61B 8/4488** (2013.01); **A61B 8/461** (2013.01); **A61B 8/488** (2013.01); **A61B 8/5207** (2013.01); **A61B 8/546** (2013.01); **B06B 1/0215** (2013.01); **B06B 1/0238** (2013.01); **B06B 1/0629** (2013.01); **B06B 1/0662** (2013.01); **B06B 1/0692** (2013.01); **G01S 7/521** (2013.01); **G01S 7/52046** (2013.01); **G01S 7/52079** (2013.01); **G01S 15/8925** (2013.01); **H01L 41/053** (2013.01); **H01L 41/0805** (2013.01); **H01L 41/098** (2013.01); **H01L 41/0973** (2013.01); **A61B 8/4427** (2013.01); **A61B 8/4472** (2013.01); **B06B 2201/76** (2013.01)

(58) **Field of Classification Search**
CPC . G01S 15/8925; B06B 1/0629; B06B 1/0692; B06B 1/0662; B06B 1/0238; B06B 1/0215; A61B 8/4494; A61B 8/0883; A61B 8/145; A61B 8/4483; A61B 8/4488; A61B 8/461; A61B 8/488; A61B 8/5207; A61B 8/546
See application file for complete search history.

(56) **References Cited**
U.S. PATENT DOCUMENTS
4,211,949 A 7/1980 Brisken et al.
4,281,298 A 7/1981 Gounji et al.
4,375,042 A 2/1983 Marcus
4,445,063 A 4/1984 Smith
4,517,842 A 5/1985 Twomey et al.
4,668,906 A 5/1987 Ekstrand
4,731,865 A 3/1988 Sievenpiper
5,520,187 A 5/1996 Snyder
5,605,154 A 2/1997 Ries et al.
5,825,117 A 10/1998 Ossmann et al.
5,969,621 A * 10/1999 Getman B06B 1/0622
310/334
6,023,977 A 2/2000 Langdon et al.
6,051,895 A 4/2000 Mercier
6,083,168 A 7/2000 Hossack et al.
6,108,121 A 8/2000 Mansell et al.
6,359,367 B1 3/2002 Sumanaweera et al.
7,005,776 B1 2/2006 Iino et al.
7,382,635 B2 6/2008 Noda
7,532,093 B1 5/2009 Pulskamp et al.
8,004,158 B2 8/2011 Hielscher
8,626,295 B2 1/2014 Doron et al.
9,479,875 B2 10/2016 Hall et al.
10,106,397 B1 10/2018 Kim et al.
2001/0005776 A1 6/2001 Holley et al.
2003/0178914 A1 9/2003 Ogawa et al.
2003/0181814 A1 9/2003 Ji et al.
2004/0195937 A1 * 10/2004 Matsubara H03H 9/02102
310/320
2005/0025377 A1 2/2005 Avinash et al.
2005/0134574 A1 6/2005 Hill
2005/0148132 A1 7/2005 Wodnicki
2005/0228282 A1 10/2005 Wang et al.
2006/0113866 A1 6/2006 Ganor
2006/0122486 A1 6/2006 Tamez-Pena et al.
2006/0173313 A1 8/2006 Liu et al.
2007/0103697 A1 5/2007 Degertekin
2007/0167752 A1 7/2007 Proulx et al.
2007/0197922 A1 8/2007 Bradley et al.
2007/0205698 A1 9/2007 Chaggares et al.
2008/0255451 A1 10/2008 Cohen et al.
2009/0001853 A1 1/2009 Adachi et al.
2009/0250729 A1 10/2009 Lemmerhirt et al.
2010/0020645 A1 1/2010 Wodnicki et al.
2010/0168583 A1 1/2010 Dausch
2010/0256501 A1 10/2010 Degertekin
2010/0266186 A1 10/2010 Hebrank et al.
2010/0327695 A1 12/2010 Goel et al.
2011/0051461 A1 3/2011 Buchwald et al.
2011/0249878 A1 10/2011 Pagoulatos et al.
2012/0116220 A1 5/2012 Burcher et al.
2012/0127136 A1 5/2012 Schneider et al.
2012/0146642 A1 6/2012 Du
2012/0187508 A1 7/2012 Adler et al.
2012/0289897 A1 11/2012 Friend et al.
2013/0039147 A1 2/2013 Witte et al.
2013/0293065 A1 11/2013 Hajati et al.
2013/0294201 A1 11/2013 Hajati
2013/0303919 A1 11/2013 Corl
2014/0019072 A1 1/2014 Alles
2014/0024928 A1 1/2014 Boctor et al.
2014/0117812 A1 5/2014 Hajati
2014/0219063 A1 8/2014 Hajati et al.
2014/0328504 A1 11/2014 Stephanou et al.
2014/0355377 A1 12/2014 Hiriyannaiah
2015/0023561 A1 1/2015 Hamilton
2015/0097468 A1 4/2015 Hajati et al.
2015/0160322 A1 6/2015 Matthews
2015/0265245 A1 9/2015 von Ramm
2015/0333730 A1 * 11/2015 Meltaas H03H 9/175
310/321
2016/0107194 A1 * 4/2016 Panchawagh G10K 11/26
367/140
2016/0136686 A1 5/2016 Brock-Fisher
2016/0211828 A1 7/2016 Simmonds et al.
2016/0262725 A1 9/2016 Boser et al.
2016/0288168 A1 10/2016 Hynynen et al.
2017/0000461 A1 1/2017 Wong et al.
2017/0224312 A1 8/2017 Call et al.
2017/0262598 A1 9/2017 Petkov et al.
2017/0322290 A1 11/2017 Ng et al.
2017/0328870 A1 11/2017 Garlepp et al.
2017/0368574 A1 12/2017 Sannoura et al.
2018/0154393 A1 6/2018 Viegas et al.
2018/0154394 A1 6/2018 Haque et al.
2018/0192999 A1 7/2018 Song et al.
2019/0176193 A1 6/2019 Shulepov et al.
2019/0184426 A1 6/2019 Kojima et al.
2019/0316957 A1 10/2019 Akkaraju et al.
2019/0316958 A1 10/2019 Akkaraju et al.
FOREIGN PATENT DOCUMENTS
WO WO-2015131083 A1 9/2015
WO WO-2017216139 A1 12/2017
WO WO-2018102223 A1 6/2018
WO WO-2018102621 A1 6/2018
WO WO-2018102622 A1 6/2018
WO WO-2019199397 A1 10/2019
WO WO-2019199398 A1 10/2019
WO WO-2019226547 A1 11/2019
WO WO-2020028580 A1 2/2020
WO WO-2020068473 A1 4/2020
WO WO-2020139775 A1 7/2020
OTHER PUBLICATIONS
PCT/US2019/021501 International Search Report and Written Opinion dated Jul. 12, 2019.
PCT/US2019/021515 International Search Report and Written Opinion dated May 31, 2019.
PCT/US2019/033119 International Search Report and Written Opinion dated Aug. 9, 2019.

(56)

References Cited

OTHER PUBLICATIONS

- PCT/US2019/044528 International Search Report and Written Opinion dated Oct. 16, 2019.
- U.S. Appl. No. 15/951,118 Office Action dated Sep. 20, 2019.
- U.S. Appl. No. 15/951,121 Office Action dated May 6, 2019.
- U.S. Appl. No. 15/951,121 Office Action dated Nov. 19, 2019.
- PCT/US2017/064090 International Search Report and Written Opinion dated Mar. 28, 2018.
- PCT/US2017/064091 International Search Report and Written Opinion dated Mar. 28, 2018.
- PCT/US2019/068004 International Search Report and Written Opinion dated Apr. 21, 2020.
- Yipeng Lu, Amir Heidari, Stefon Shelton, Andre Guedes and David A. Horsley, "High Frequency Piezoelectric Micromachined Ultrasonic Transducer Array for Intravascular Ultrasound Imaging", University of California, Davis, USA, Jan. 26-30, 2014.
- Arman Hajati, Dimitre Latev, Deane Gardner, Azadeh Hajati, Darren Imai et al., "Three-dimensional micro electromechanical system piezoelectric ultrasound transducer", *Appl. Phys. Lett.* 101, 253101 (2012); doi: 10.1063/1.4772469.
- A. Guedes, S. Shelton, R. Przybyla, I. Izyumin, B. Boser and D.A. Horsley, "Aluminum Nitride PMUT Based on a Flexurally-Suspended Membrane", Berkeley Sensor & Actuator Center, University of California, Davis, CA, USA Berkeley Sensor & Actuator Center, University of California, Berkeley, CA, USA.
- Sang Hwui Lee, Kuan-Neng Chen, Member, IEEE, and James Jian-Qiang Lu, Fellow, IEEE, "Wafer-to-Wafer Alignment for Three-Dimensional Integration: A Review", *Journal of MicroElectroMechanical Systems*, vol. 20, No. 4, Aug. 2011, pp. 885.
- Tao Wang, Member, IEEE, and Chengkuo Lee, Member, IEEE, "Zero-Bending Piezoelectric Micromachined Ultrasonic Transducer (pMUT) With Enhanced Transmitting Performance", *Journal of Microelectromechanical Systems*, vol. 24, No. 6.
- Tao Wang, Takeshi Kobayashi, and Chengkuo Lee, Member, IEEE, "Broadband Piezoelectric Micromachined Ultrasonic Transducer (pMUT) Using Mode-Merged Design", *Proceedings of the 10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems (IEEE—NEMS 2015) Xi'an, China, Apr. 1-11, 2015.*
- Thomas L.Szabo, "Diagnostic Ultrasound Imaging: Inside Out", Elsevier Academic Press, ISBN: 0-12-680145-2, Fig 5.6 and Fig 5.7.
- David E. Dausch, Senior Member, IEEE, John B. Castellucci, Derrick R. Chou, Student Member, IEEE, and Olaf T. von Ramm, "Theory and Operation of 2-D Array Piezoelectric Micromachined Ultrasonic Transducers", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, No. 11, Nov. 2008.
- High Frequency Transducers from PZT Films, a thesis in Materials Science and Engineering by Joanna G. Mina, Pennsylvania State University, Graduate School, College of Earth and Mineral Sciences, May 2007, Fig 1-1.
- Katherine Marie Smyth, "Design and Modeling of a PZT Thin Film Based Piezoelectric Micromachined Ultrasonic Transducer (PMUT)", Massachusetts Institute of Technology Jun. 2012.
- "Introduction to B-mode imaging", Kevin Martin, Cambridge University Press, 978-0-521-75710-2-Diagnostic Ultrasound: Physics and equipment, 2nd Edition.
- "Electrical Characteristics of Ferroelectric PZT Thin Films for DRAM Applications", Reza Moazzami, Chenming Hu, William Shepherd, *IEEE Transaction on Electron Devices*, vol. 39, No. 9, Sep. 1992, p. 2044.
- "Apple's Lightning connector and you: what you should know", Joshua Goldman, CNET Sep. 19, 2012, <https://www.cnet.com/news/apples-lightning-connector-and-you-what-you-should-know/>.
- "Coherent Plane-Wave Compounding in Medical Ultrasound Imaging", RAGNHILDOVLAND, NTNU—Trondheim, Norwegian University of Science and Technology, Master of Science Thesis, Jun. 2012.
- "Synthetic Aperture Method in Ultrasound Imaging", I Trots, A Nowicki, M Lewandowski, Y Tasinkevych, Institute of Fundamental Technological Research Poland, Apr. 2011.
- "Ultrasound Beamforming and Image Formation", Jeremy J.Dahl, http://people.duke.edu/~jjd/RSNA_USbeamforming.pdf.
- "Adaptive time gain compensation for ultrasonic imaging", Pye, SD, Wild SR, McDicken Wn, *Ultrasound Medical Biology*, 1992; 18(2); 205-12.
- "Signal Conditioning Piezoelectric Sensors", Texas Instruments Application report, SLA033A—Sep. 2000.
- "Generating Nonlinear FM Chirp Waveforms for Radar", Armin W. Doerry, Sandia Report, SAND2006-5856, Sep. 2006.
- "Comparison of Tissue Harmonic Imaging with Conventional US in Abdominal Disease", Sabina Choudhry, MD et al., *Imaging & Therapeutic Technology*.
- "Piezoelectric materials for ultrasonic probes", NDTnet—Sep. 1996, vol. 1. No. 09, by M. Lach, M. Platte, A. Ries.
- "Low Cost Matching Network for Ultrasonic Transducers", M.Garcia-Rodriguez, J.Garcia-Alvarez, Y. Yanez, M.J.Garcia-Hernandez, J. Salazar, A. Turo, J.A.Chavez, *Physics Procedia* 3 (2010) 1025-1031, International Congress on Ultrasonics, Universidad de Santiago de Chile, Jan. 2009.
- "Scanning in Pain—Sonographers Seek Relief From Job-Related Hazard", Beth Orenstein, *Radiology Today*, vol. 10, No. 8, p. 24.
- "Capacitive micro machined ultrasonic transducers for medical imaging and therapy", Butrus T. Khuri-Yakub and Omer Oralkan, *J Micromech Microeng.* May 2011; 21(5):054004-054014, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3158704/>.
- "Use of Chirps in Medical Ultrasound Imaging", Sevan Harput, Ultrasound Group, School of Electronic and Electrical Engineering, University of Leeds, PhD Thesis, Dec. 2012.
- "Spectral Doppler", <http://www.echocardiographer.org/Echo%20Physics/spectral%20doppler.html>.
- "Biplane ultrasound arrays with integrated multiplexing solution for enhanced diagnostic accuracy in endorectal and transvaginal imaging", N Felix*, D Voisin, O Clade, R Dufait, Vermon, Tours—France; <http://www.vermon.com>, http://www.vermon.com/vermontpublications/Felix_UFFC_2005.pdf.
- "A reconfigurable arbitrary waveform generator using PWM modulation for ultrasound research", BioMedical Engineering Online. Amauri A Assef et al., 2013; 12:24; published on line Mar. 2013.
- "Ceramic Manufacturing Series—Poling PZT Ceramics", Mar. 16, 2016. Posted in APC Materials, Piezo Applications., <https://www.americanpiezo.com/blog/ceramic-manufacturing-series-poling-pzt-ceramics/>.
- "Design and Modeling of a PZT Thin Film Based Piezoelectric Micromachined Ultrasonic Transducer (PMUT)", Katherine Marie Smyth, MSME Thesis, MIT 2012.
- "Theory and Operation of 2D Array Piezoelectric Micromachined Transducers", David E. Dausch et al, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 55, No. 11, Nov. 2008.
- Co-pending U.S. Appl. No. 17/067,119, inventors Haque; Yusuf et al., filed Oct. 8, 2020.
- Co-pending U.S. Appl. No. 17/067,139, inventors Haque; Yusuf et al., filed Oct. 8, 2020.
- PCT/US2019/051238 International Search Report and Written Opinion dated Dec. 19, 2019.

* cited by examiner

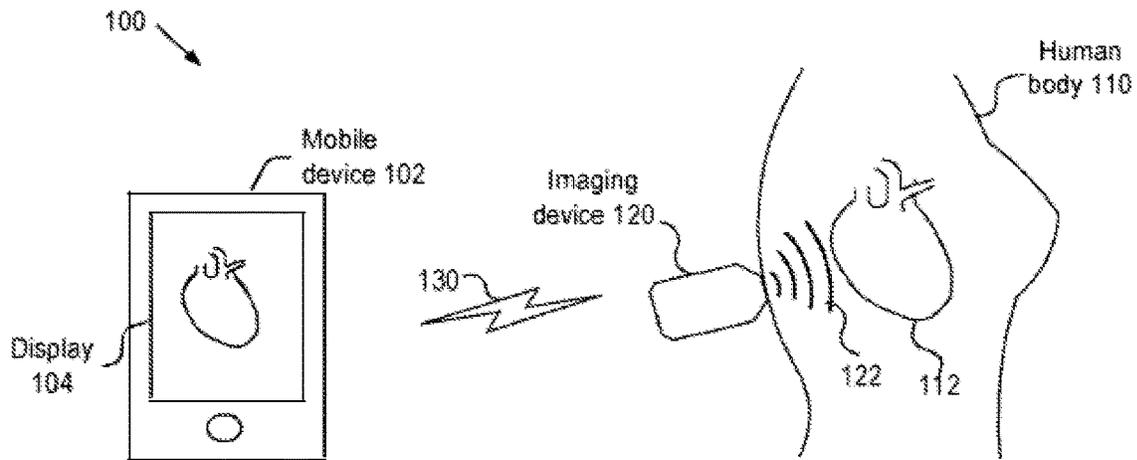


FIG. 1

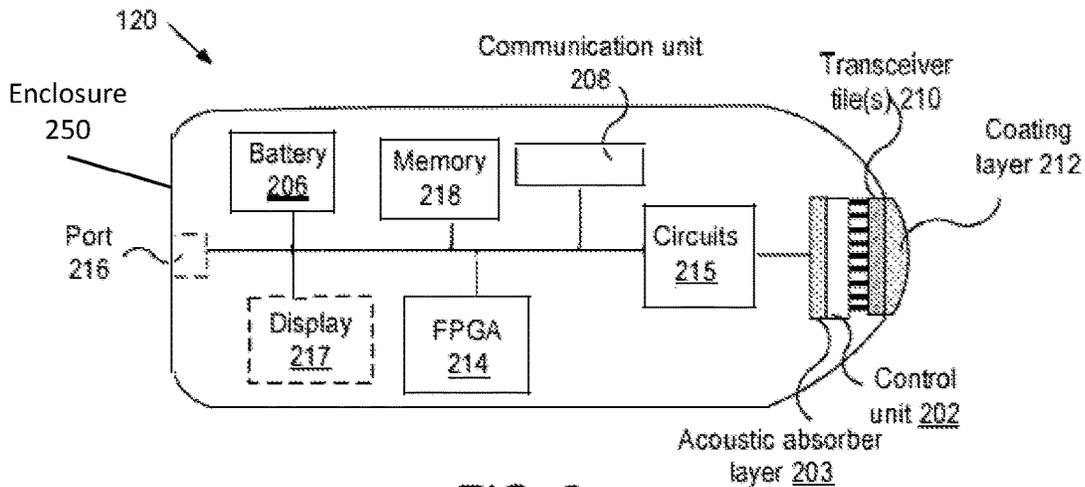


FIG. 2

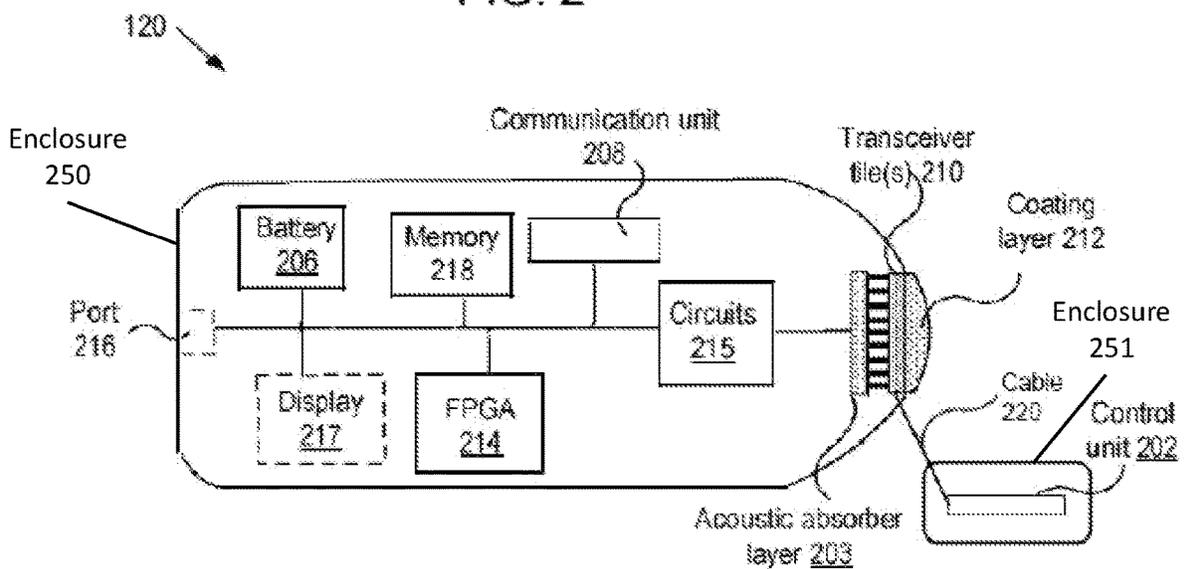
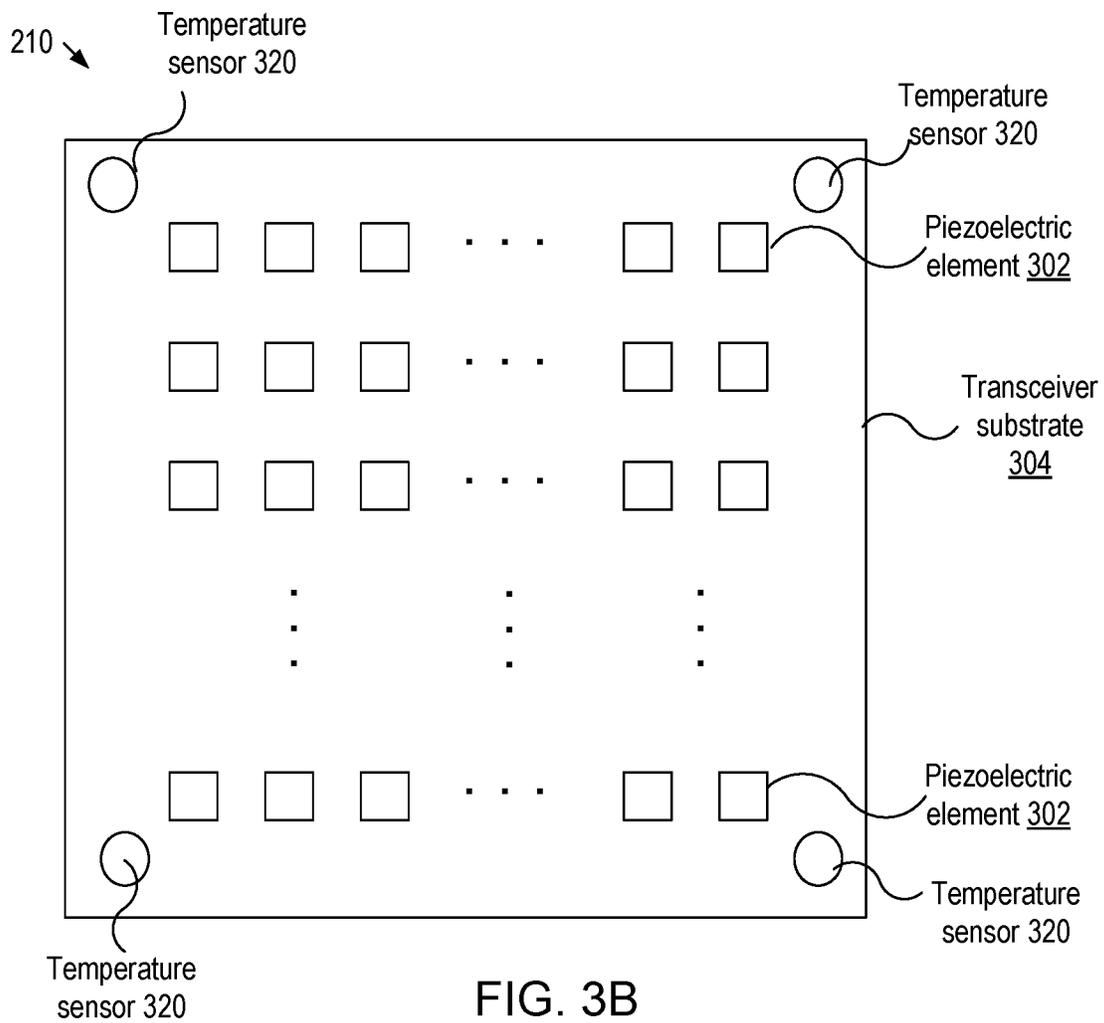
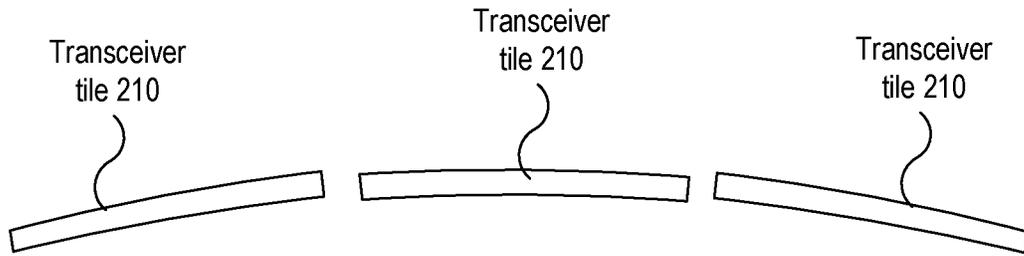


FIG. 2A



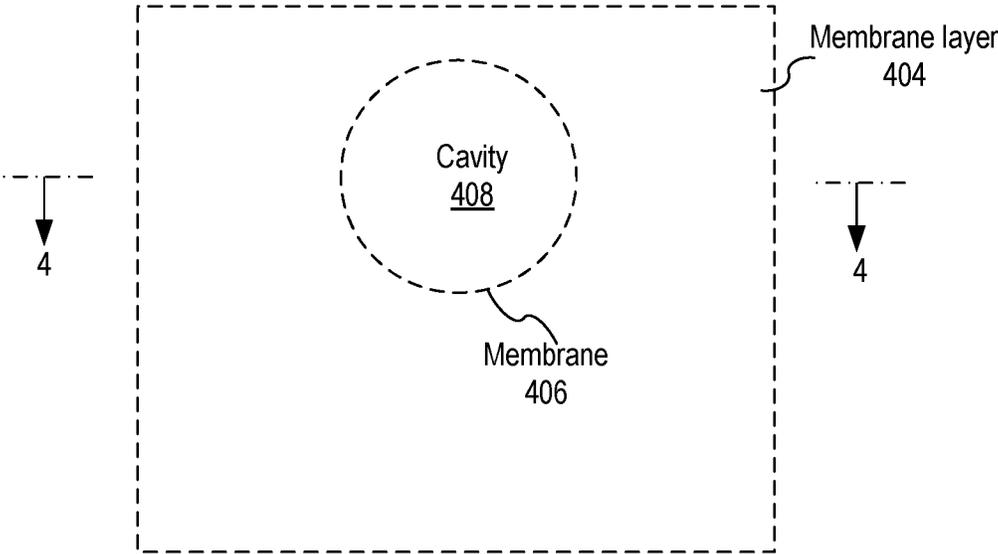


FIG. 4

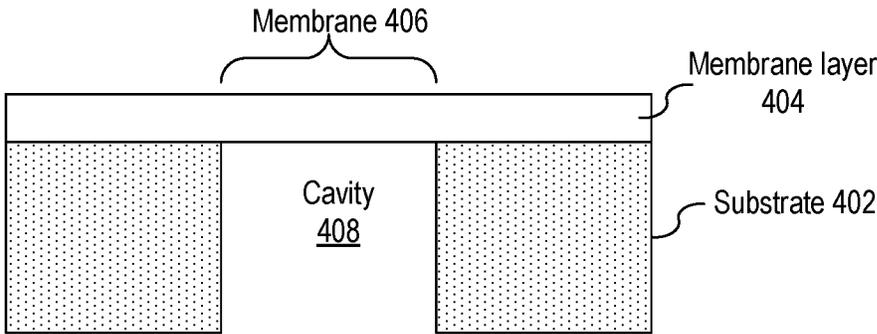


FIG. 5

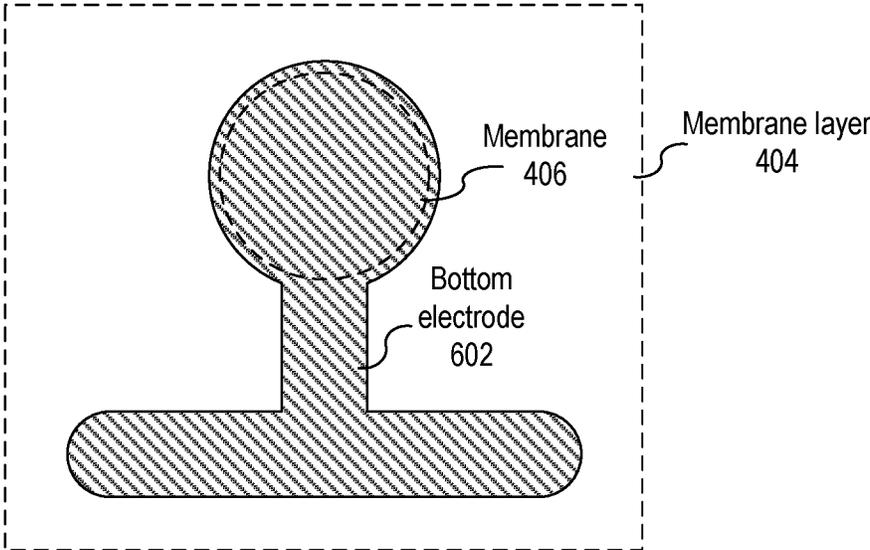


FIG. 6

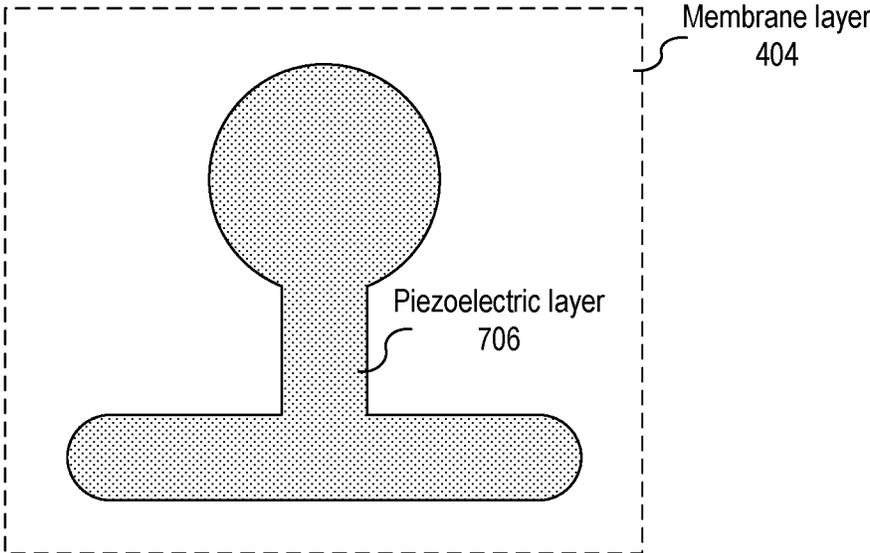


FIG. 7

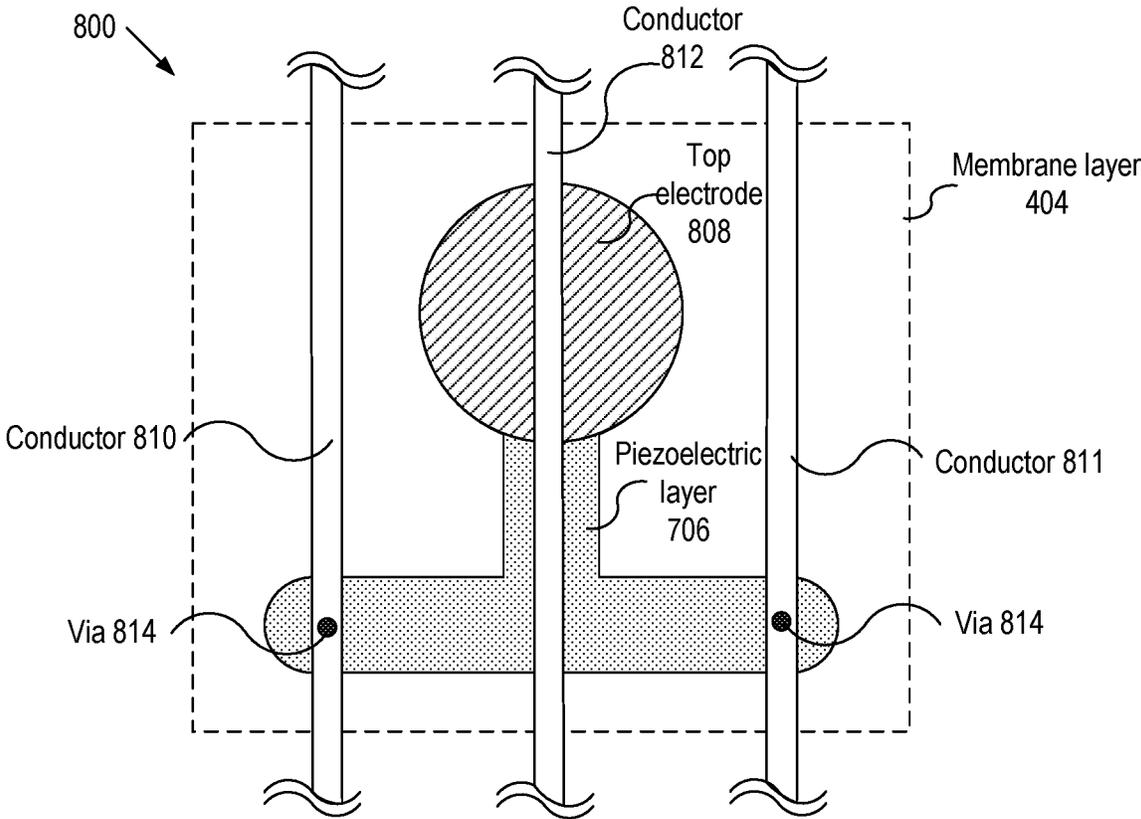


FIG. 8

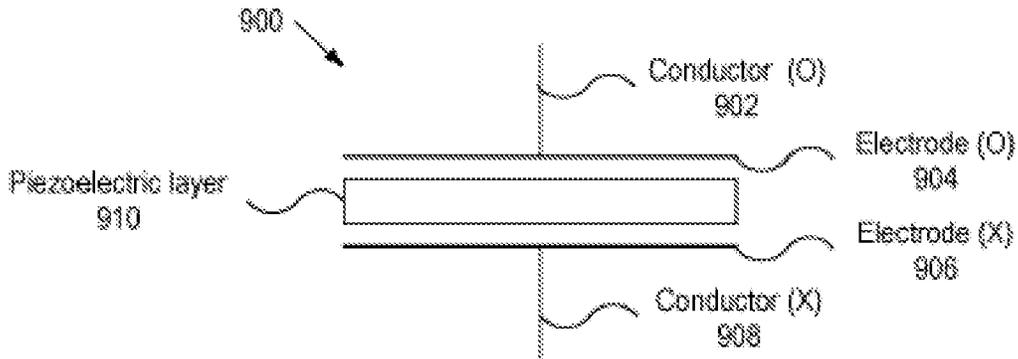


FIG. 9

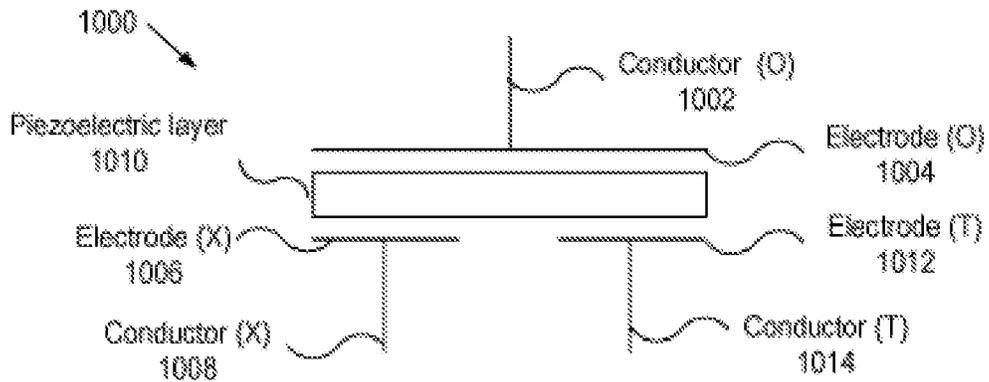


FIG. 10A

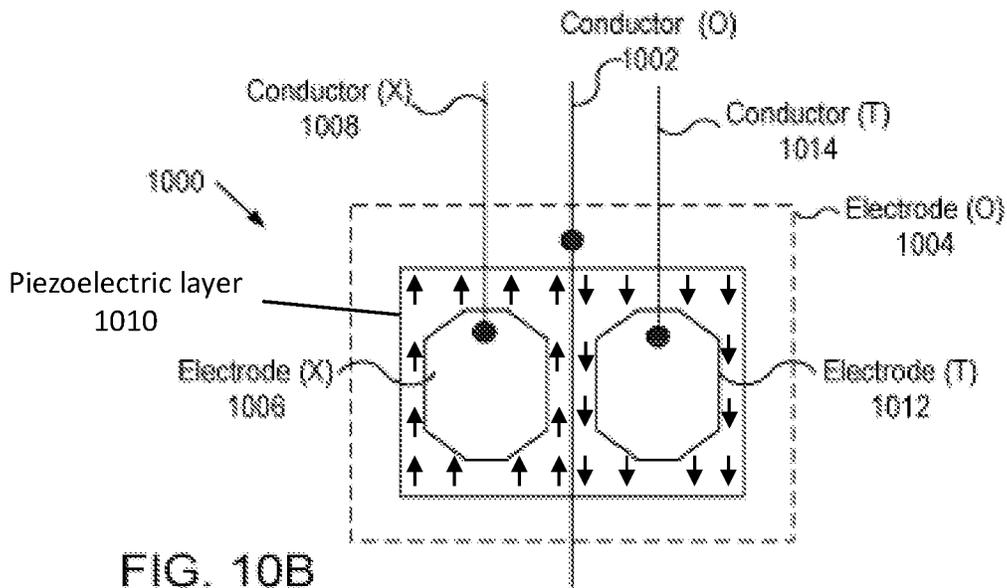


FIG. 10B

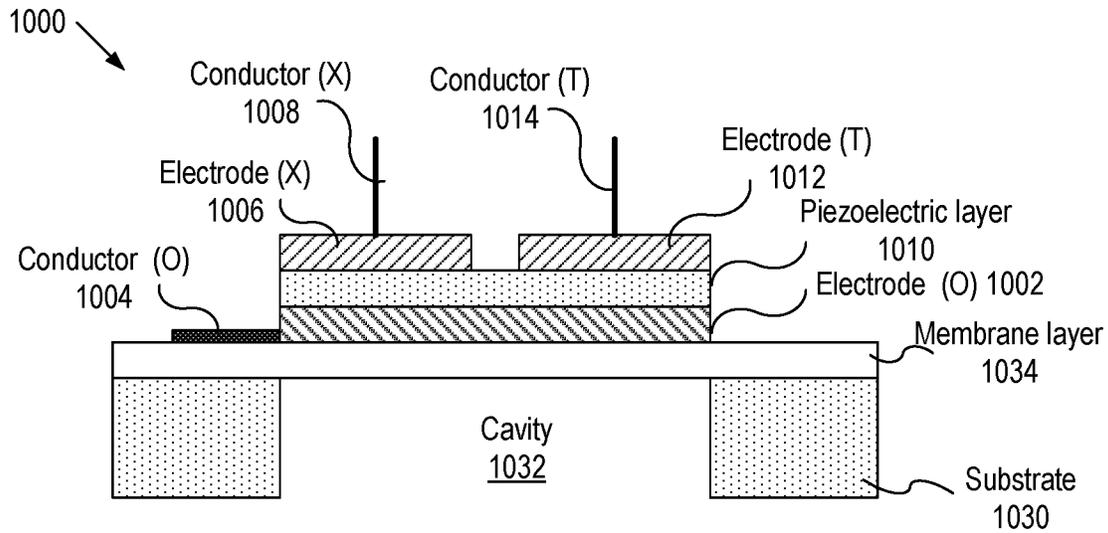


FIG. 10C

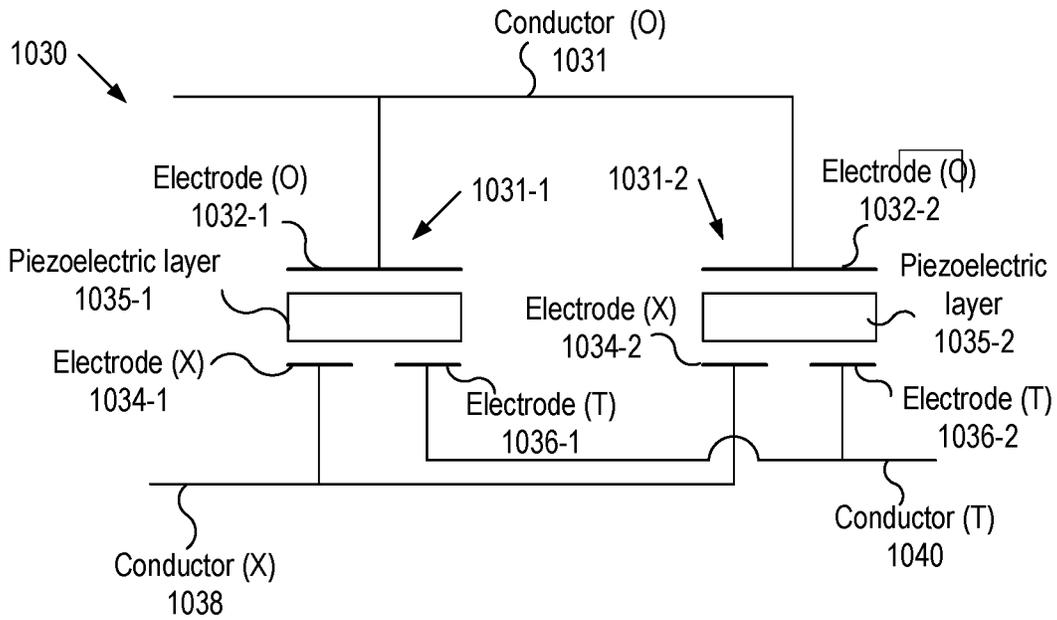


FIG. 10D

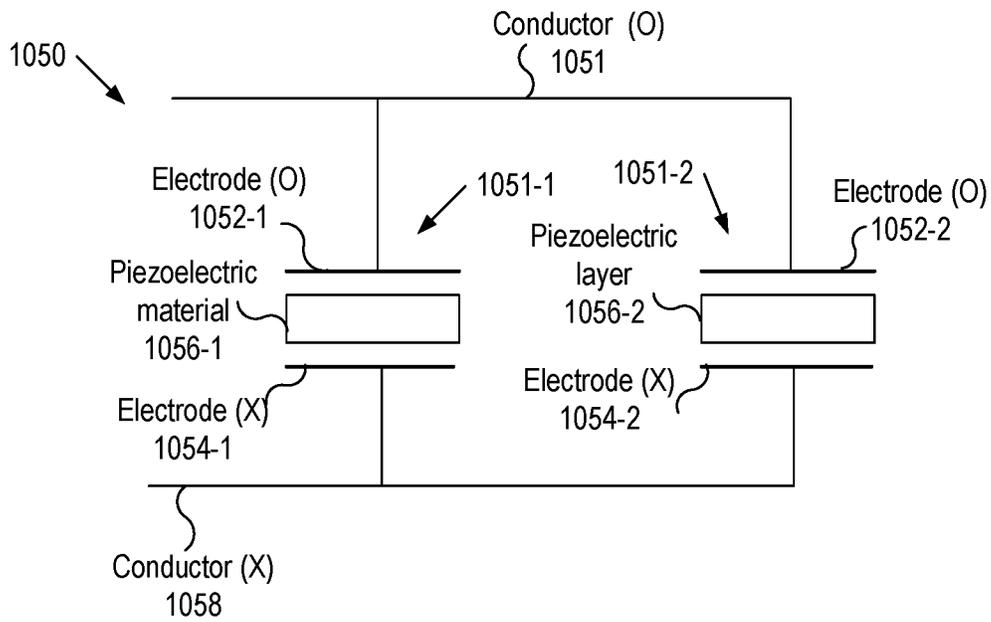


FIG. 10E

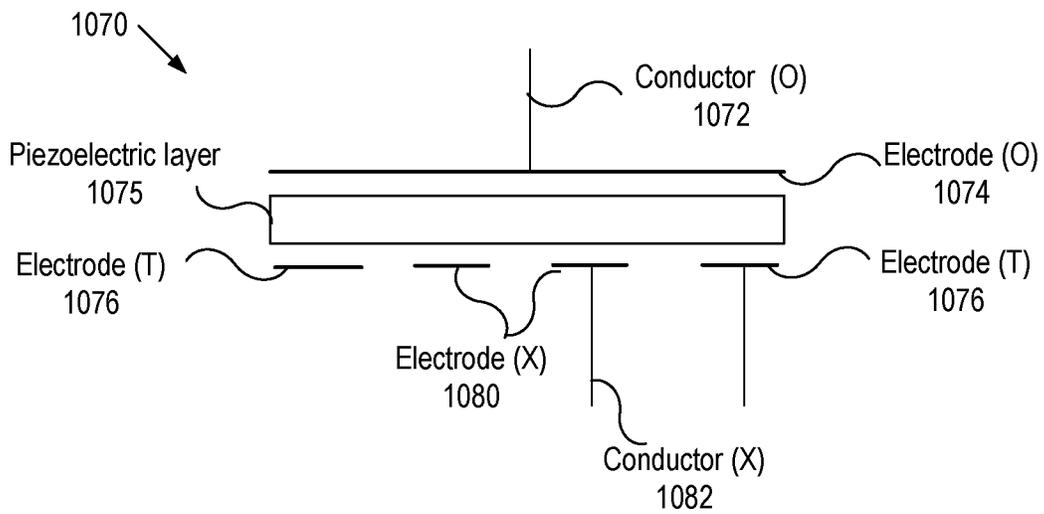


FIG. 10F

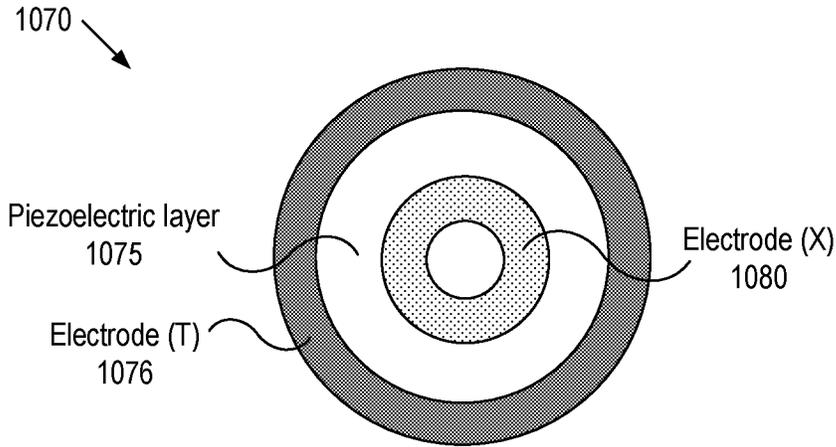


FIG. 10G

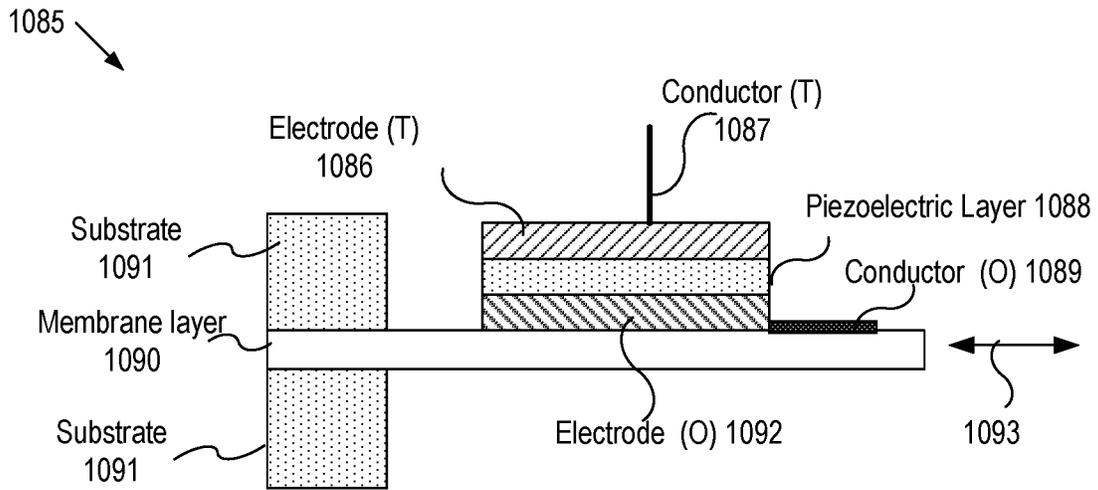


FIG. 10H

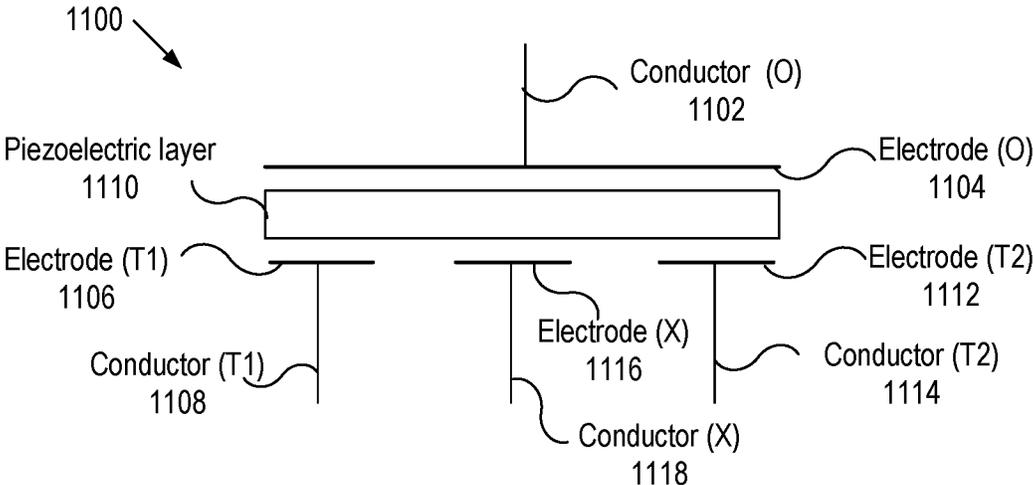


FIG. 11

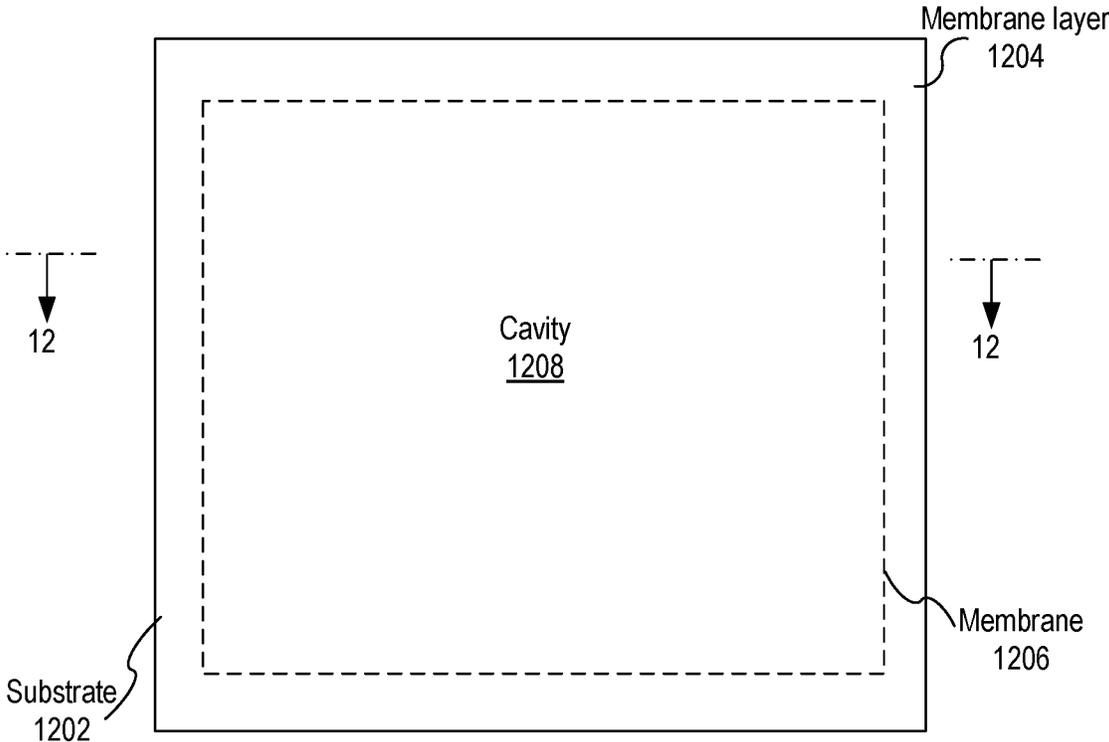


FIG. 12

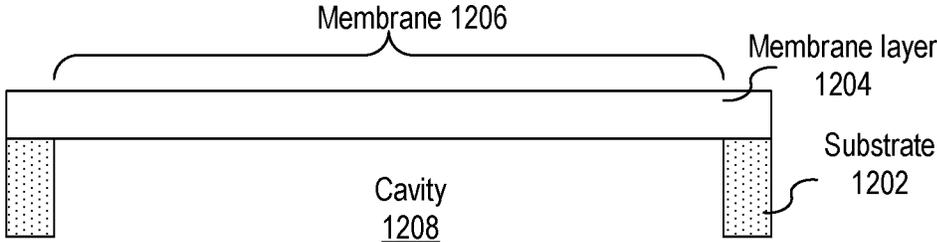


FIG. 13

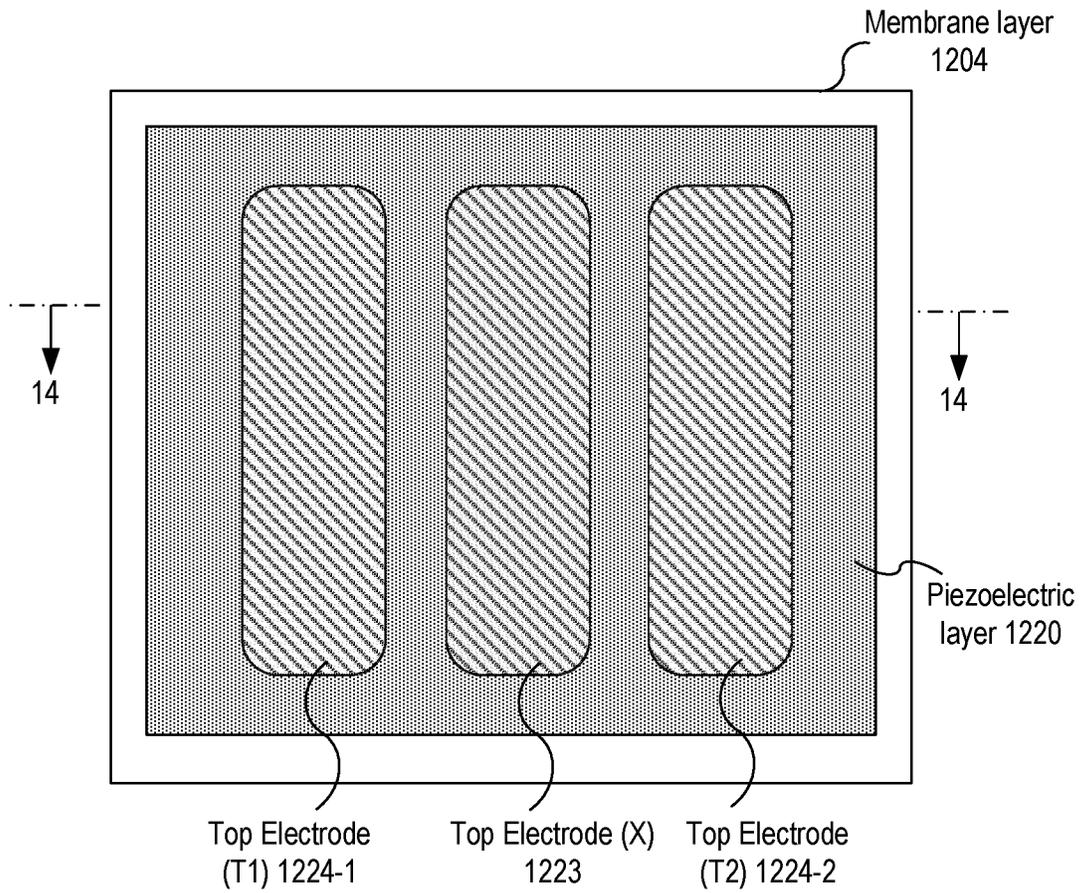


FIG. 14

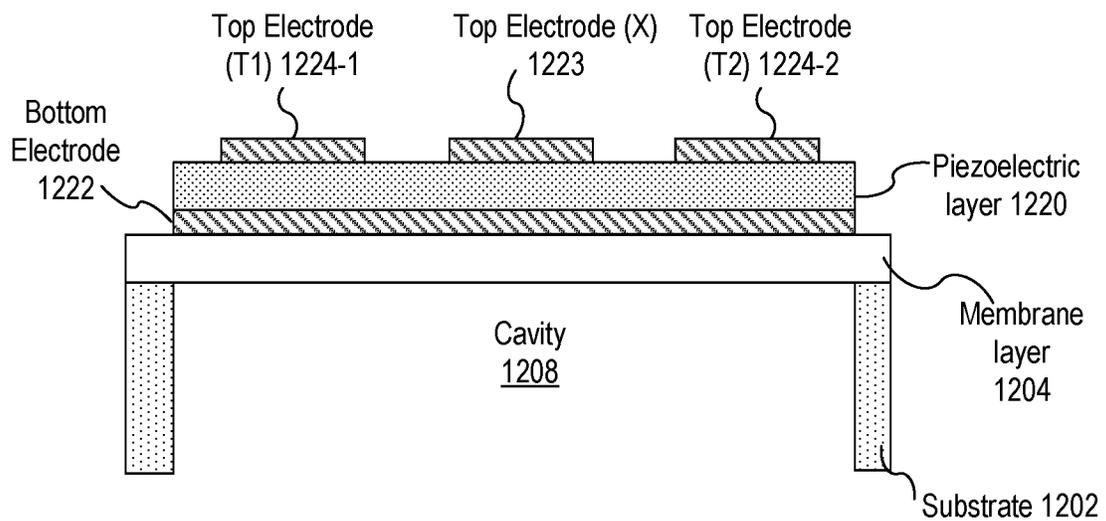


FIG. 15

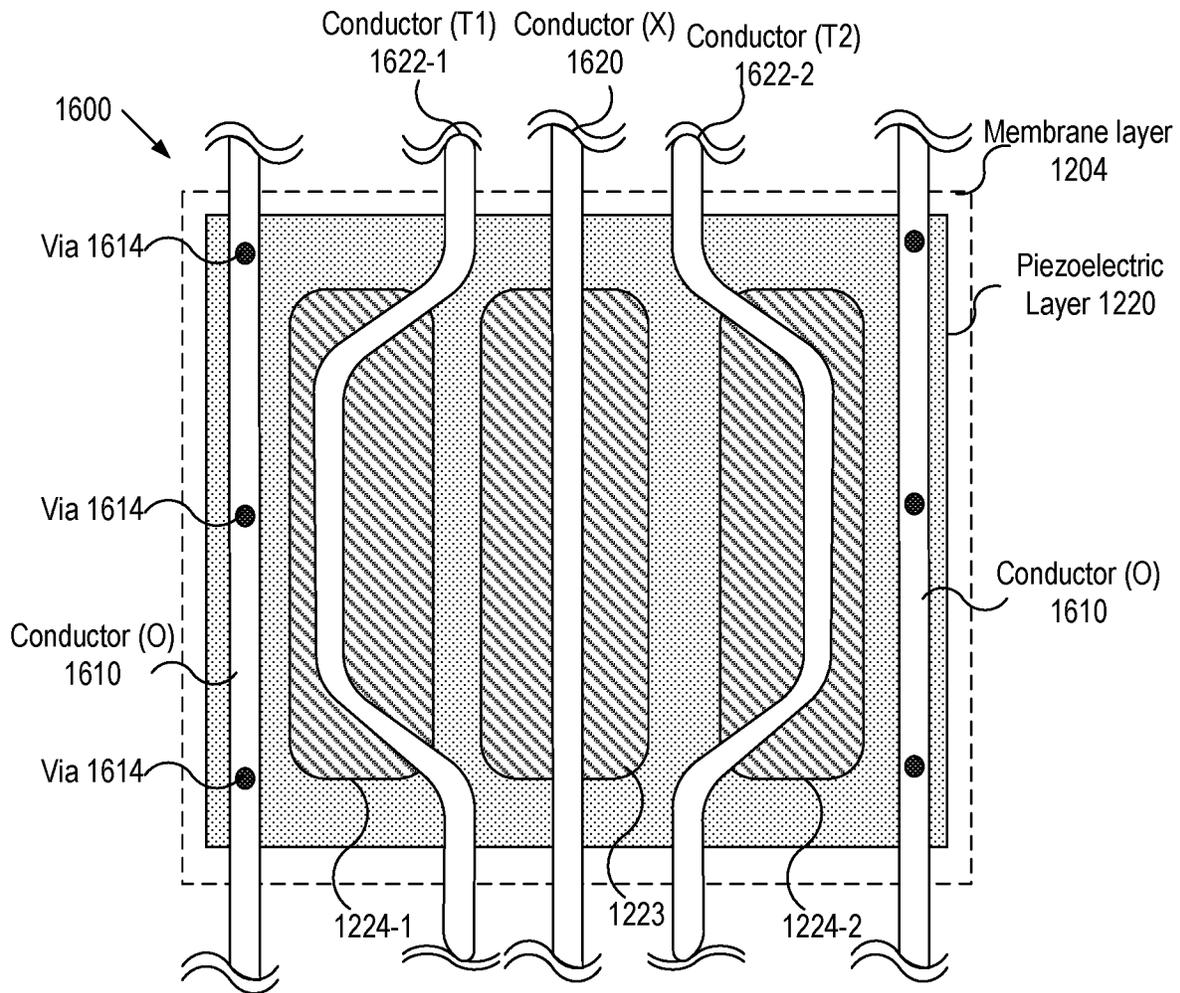


FIG. 16

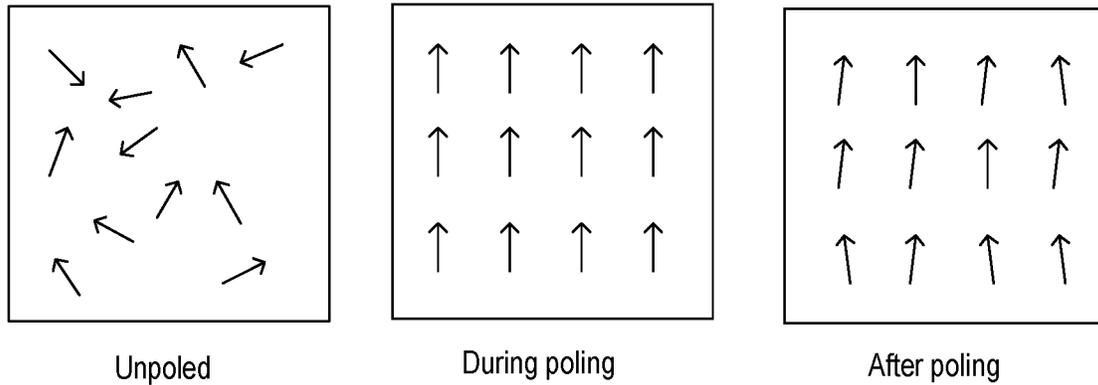


FIG. 17A

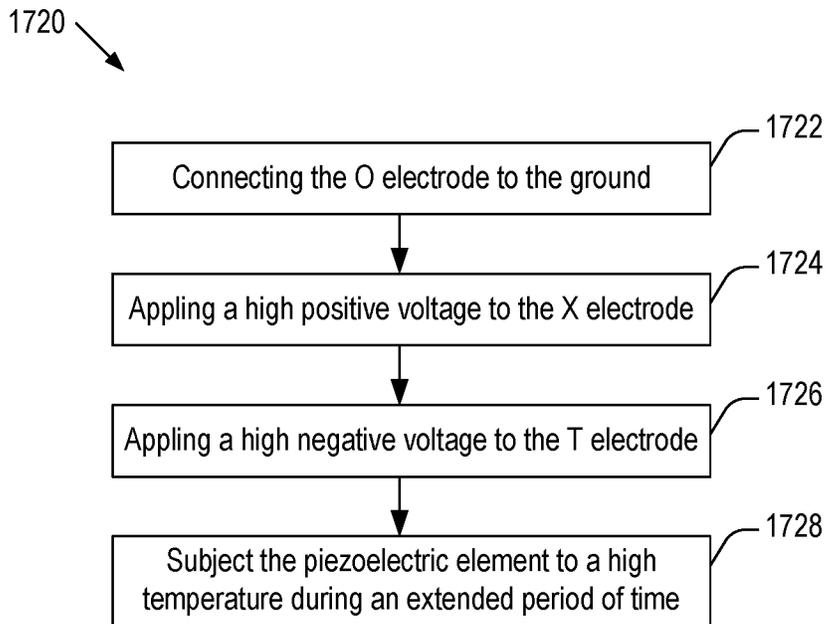
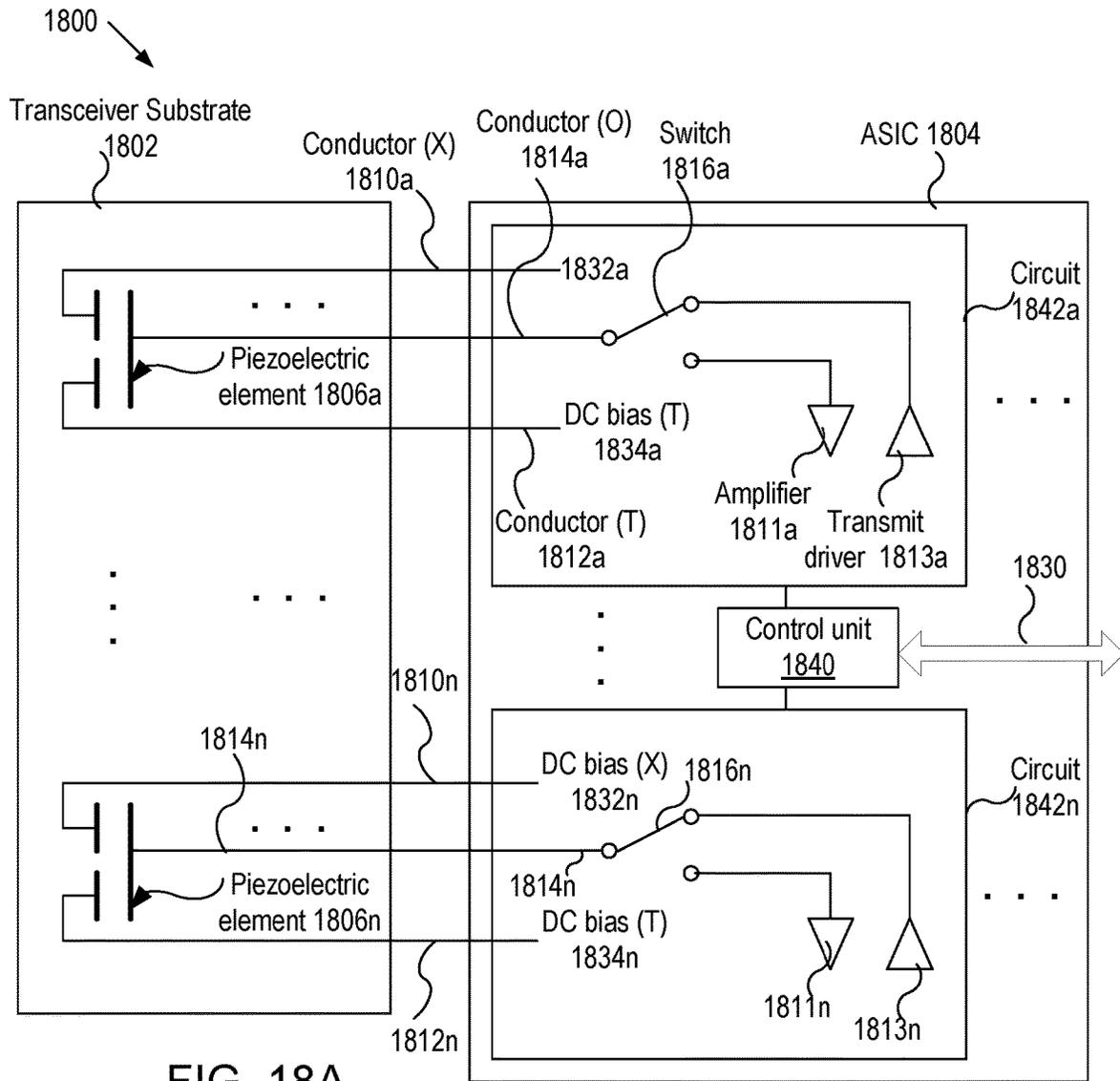


FIG. 17B



1850 ↘

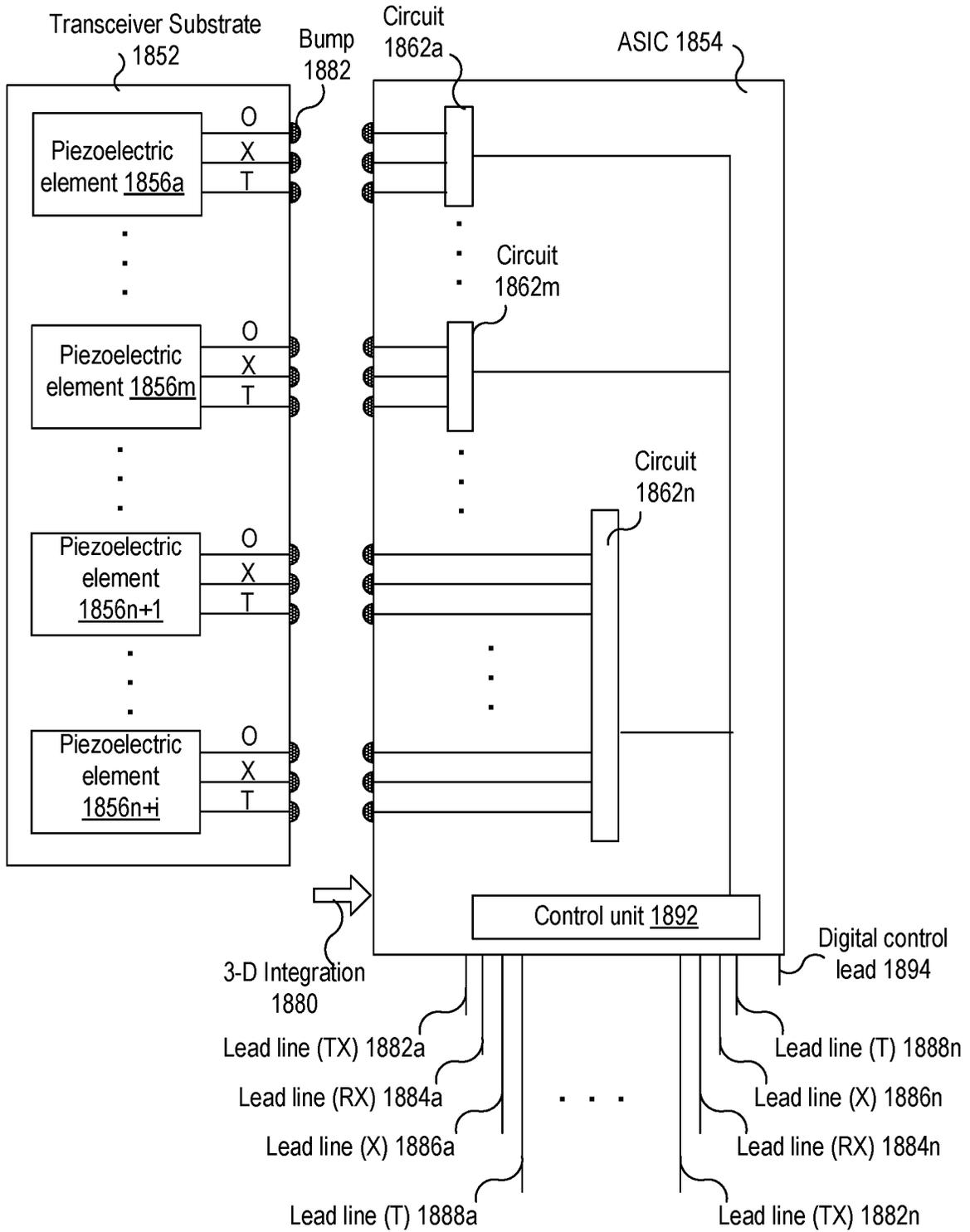


FIG. 18B

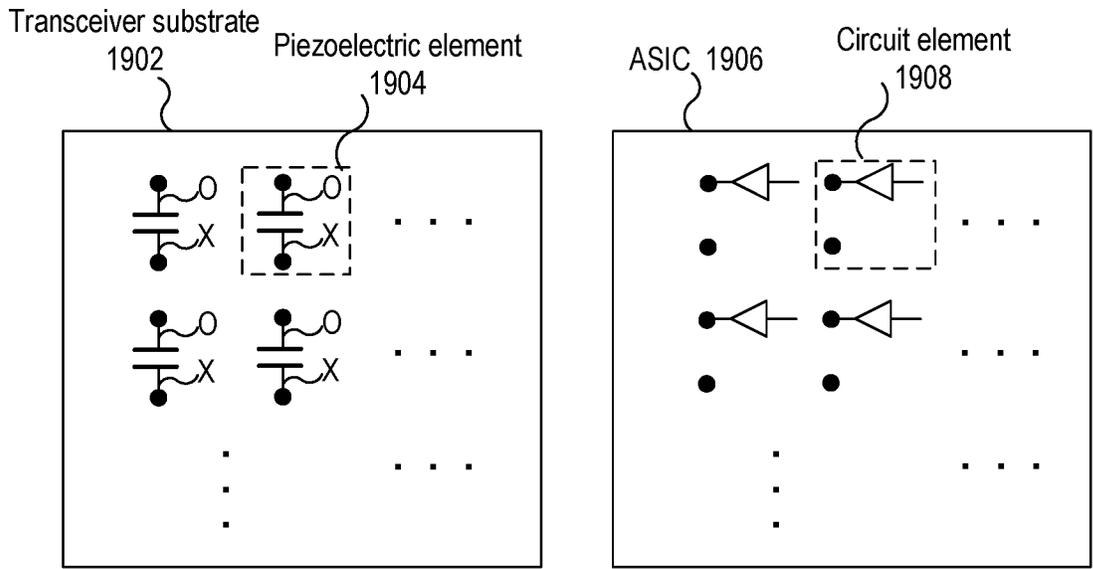


FIG. 19A-1

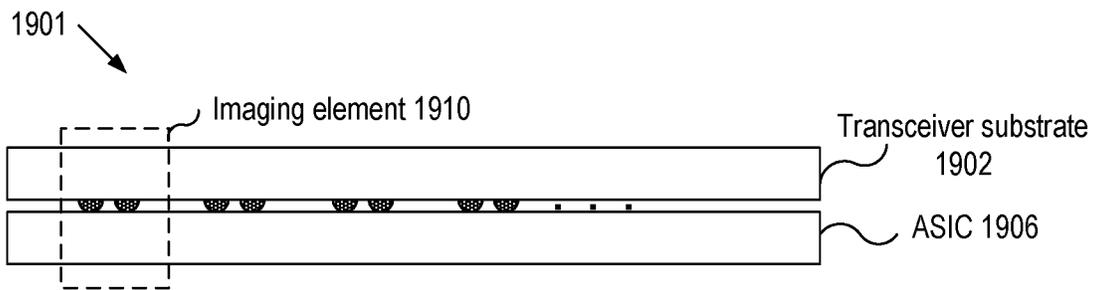


FIG. 19A-2

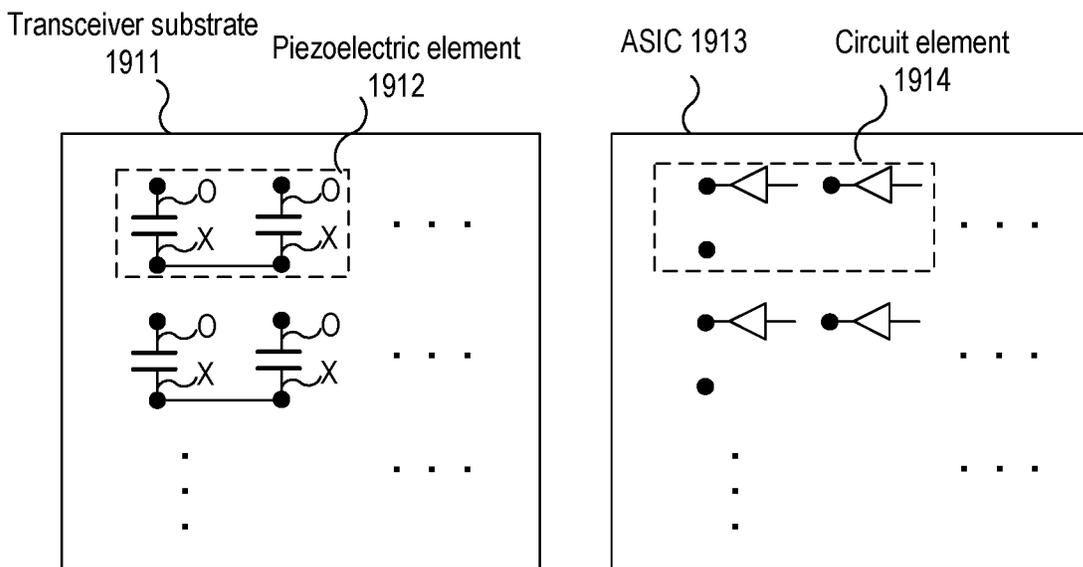


FIG. 19B-1

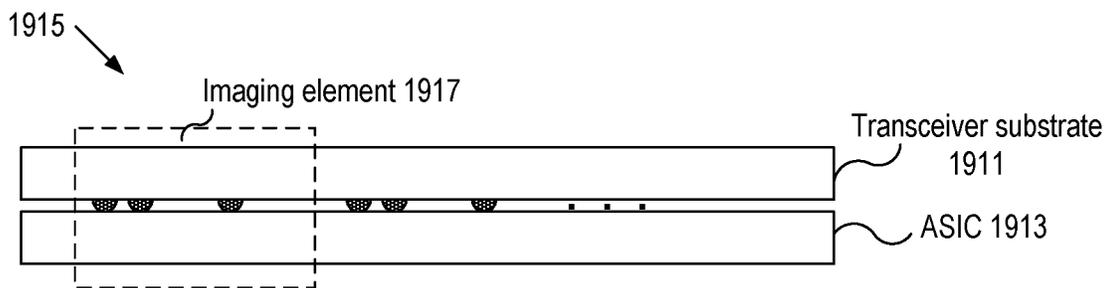


FIG. 19B-2

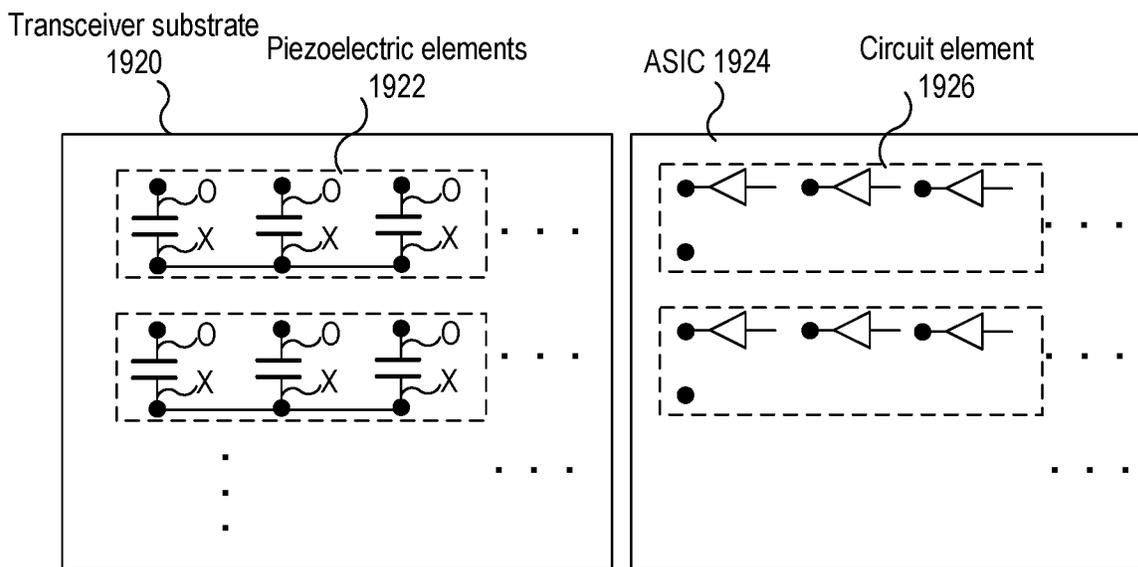


FIG. 19C

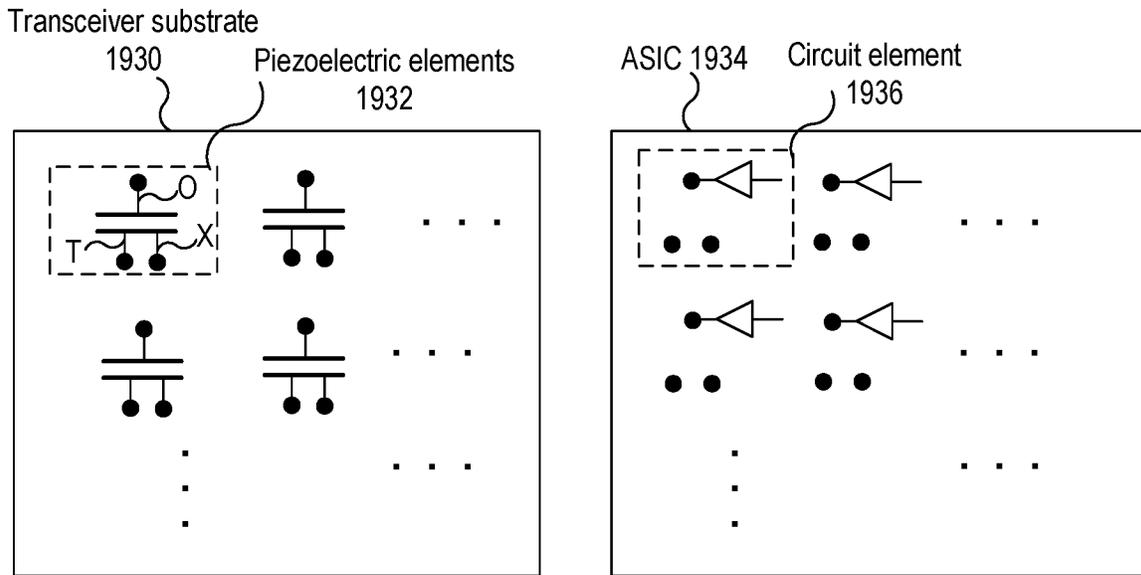


FIG. 19D

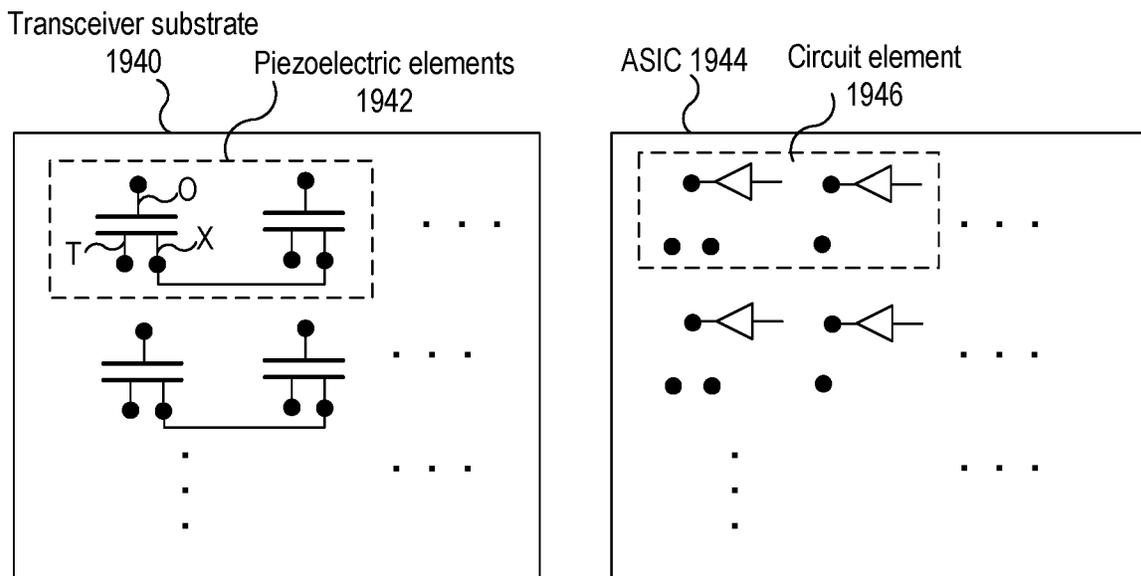


FIG. 19E

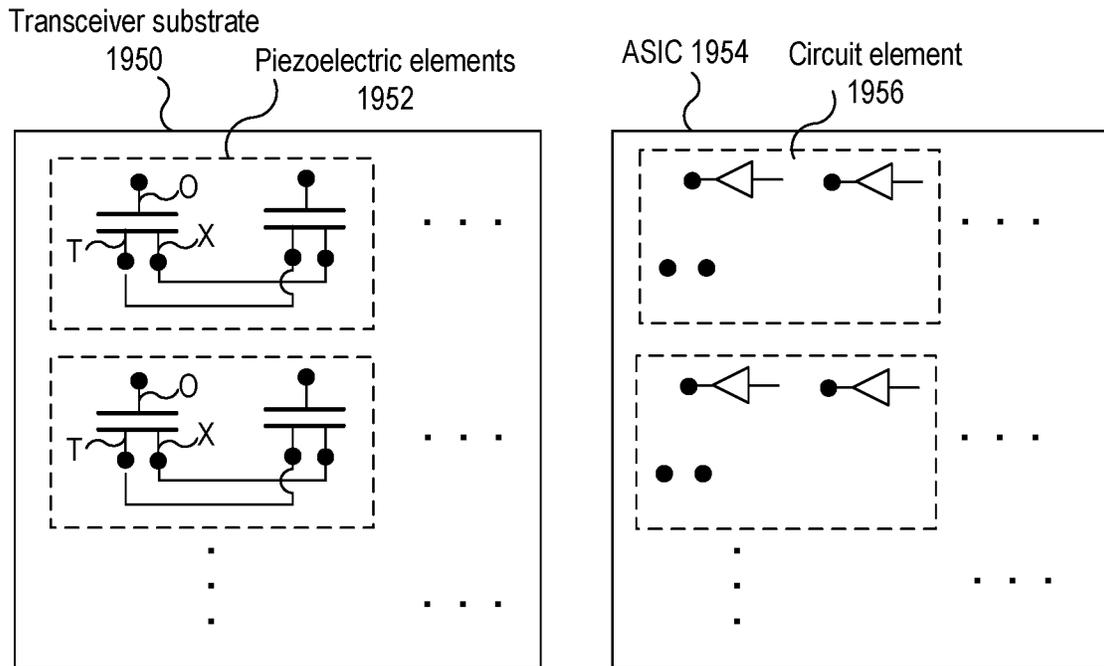


FIG. 19F

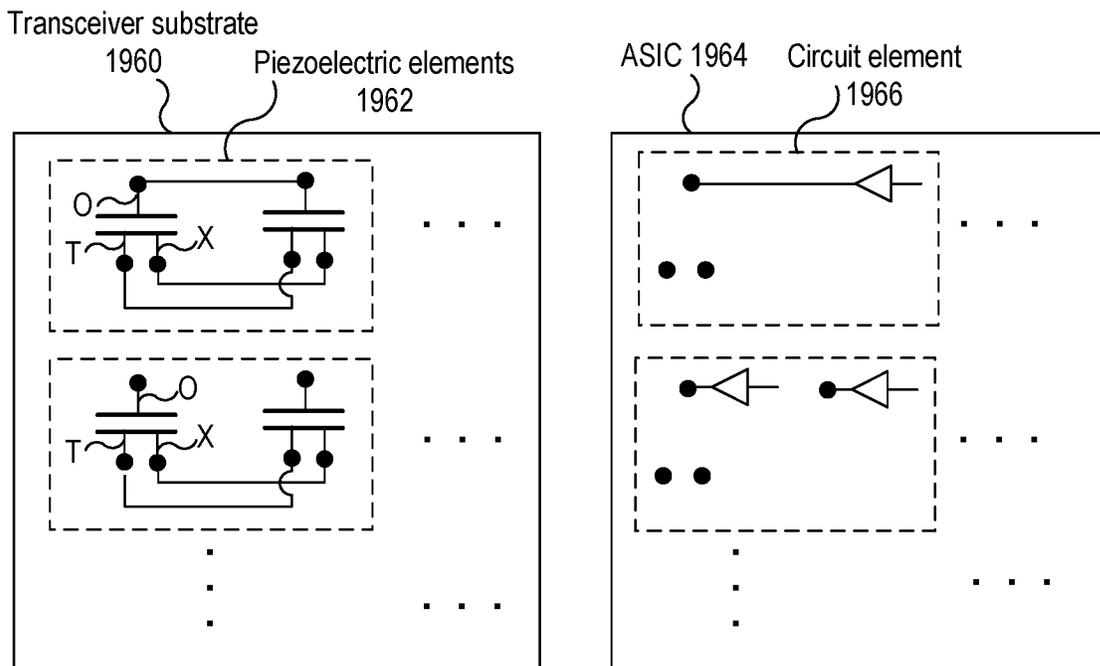


FIG. 19G

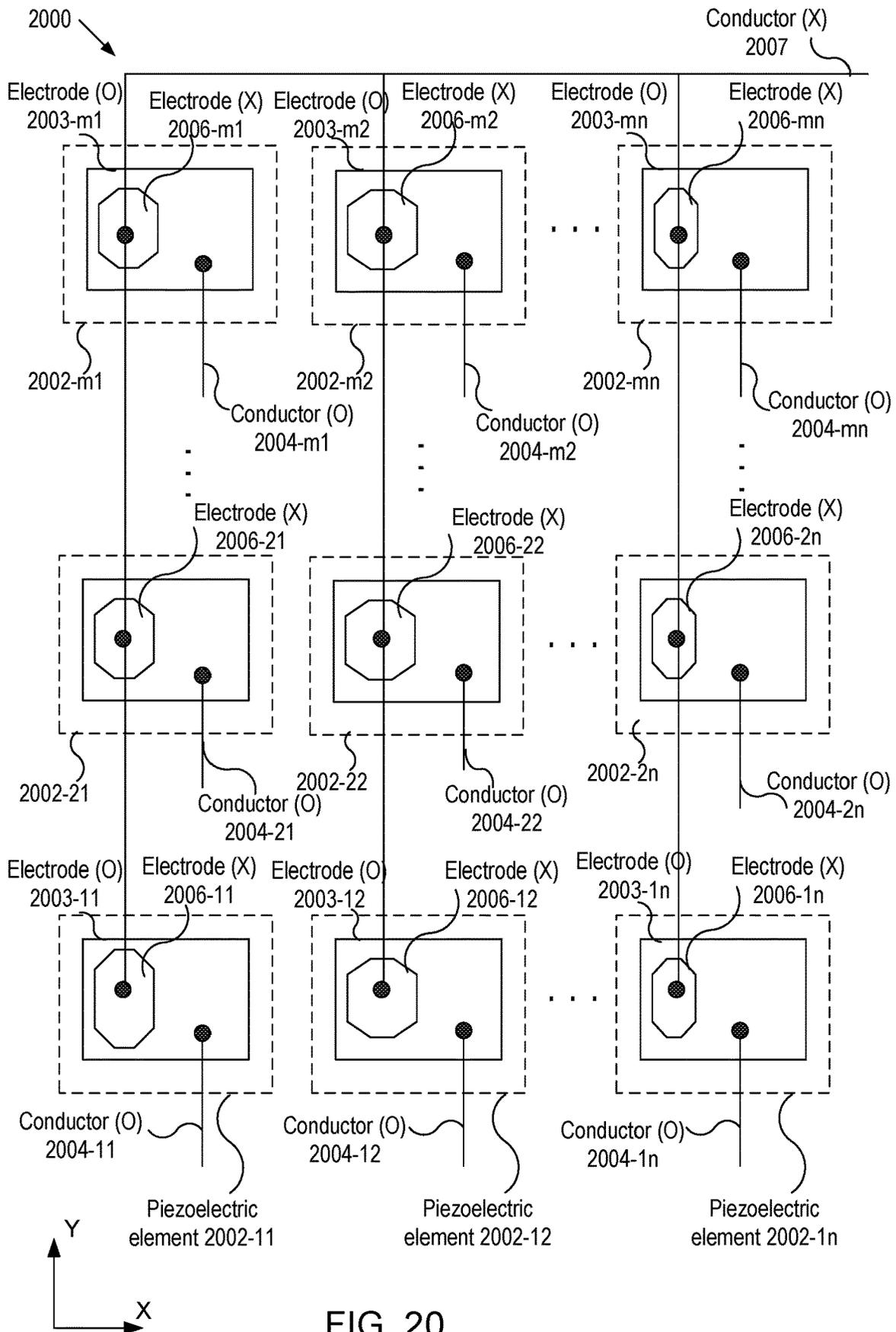
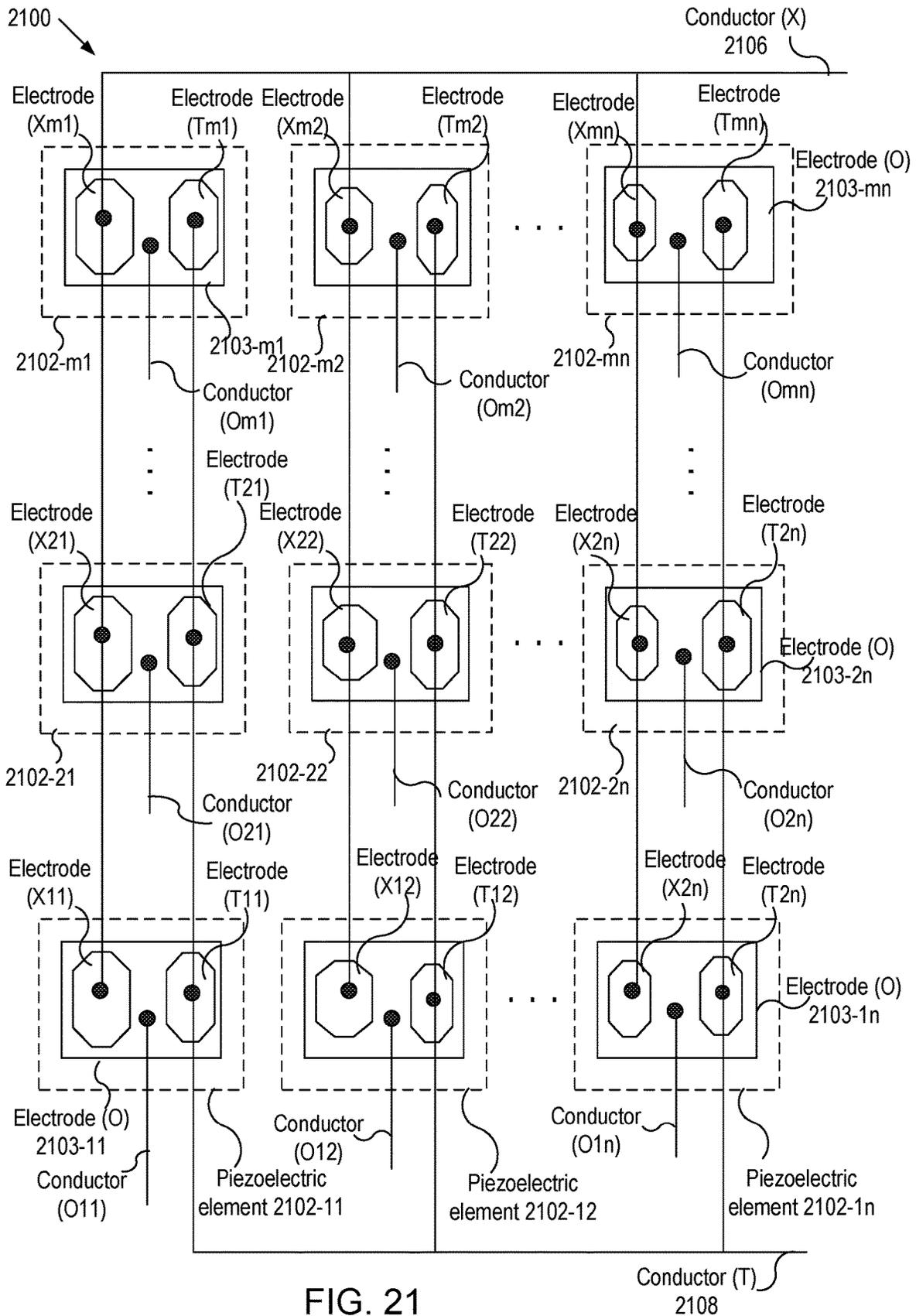


FIG. 20



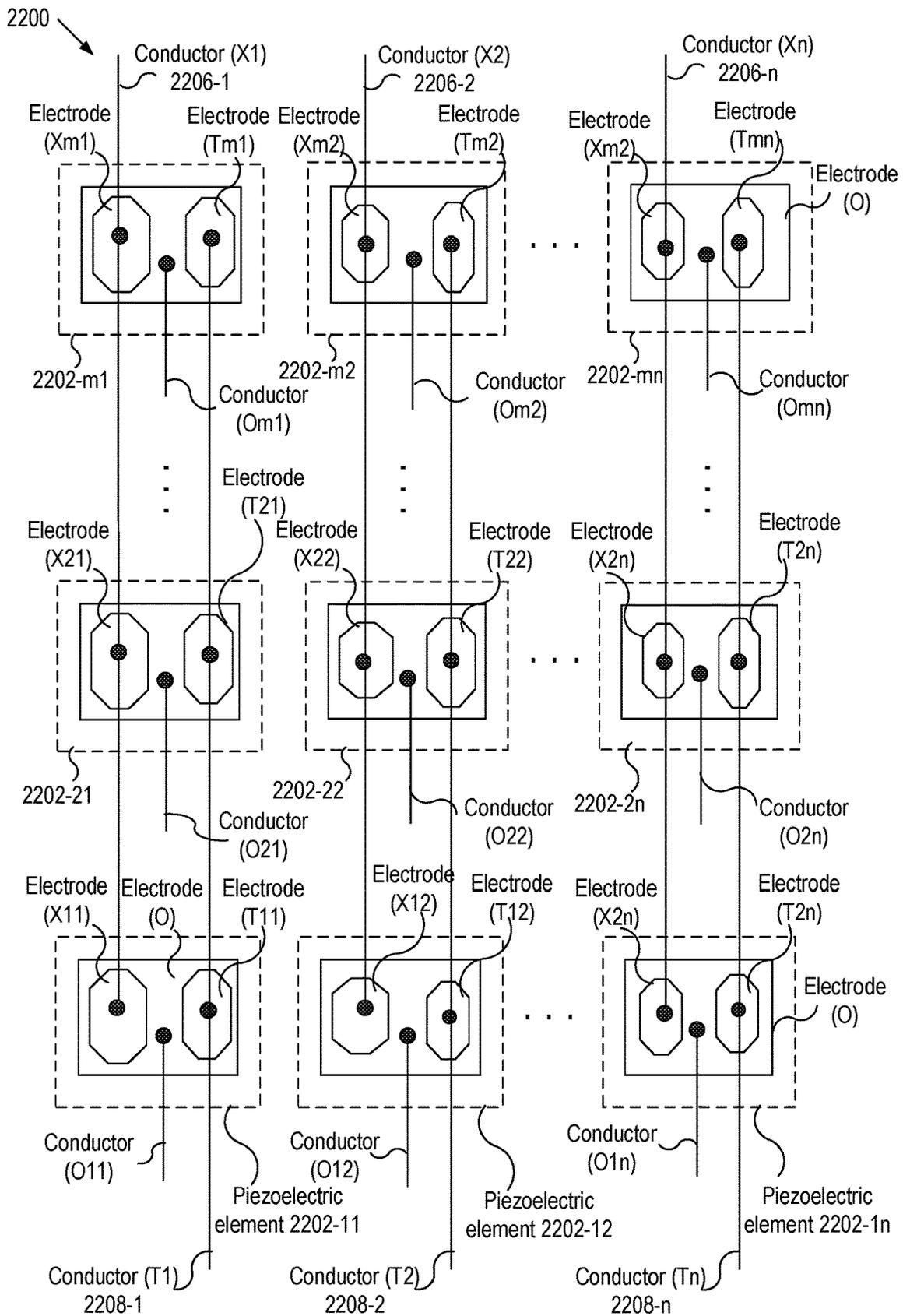
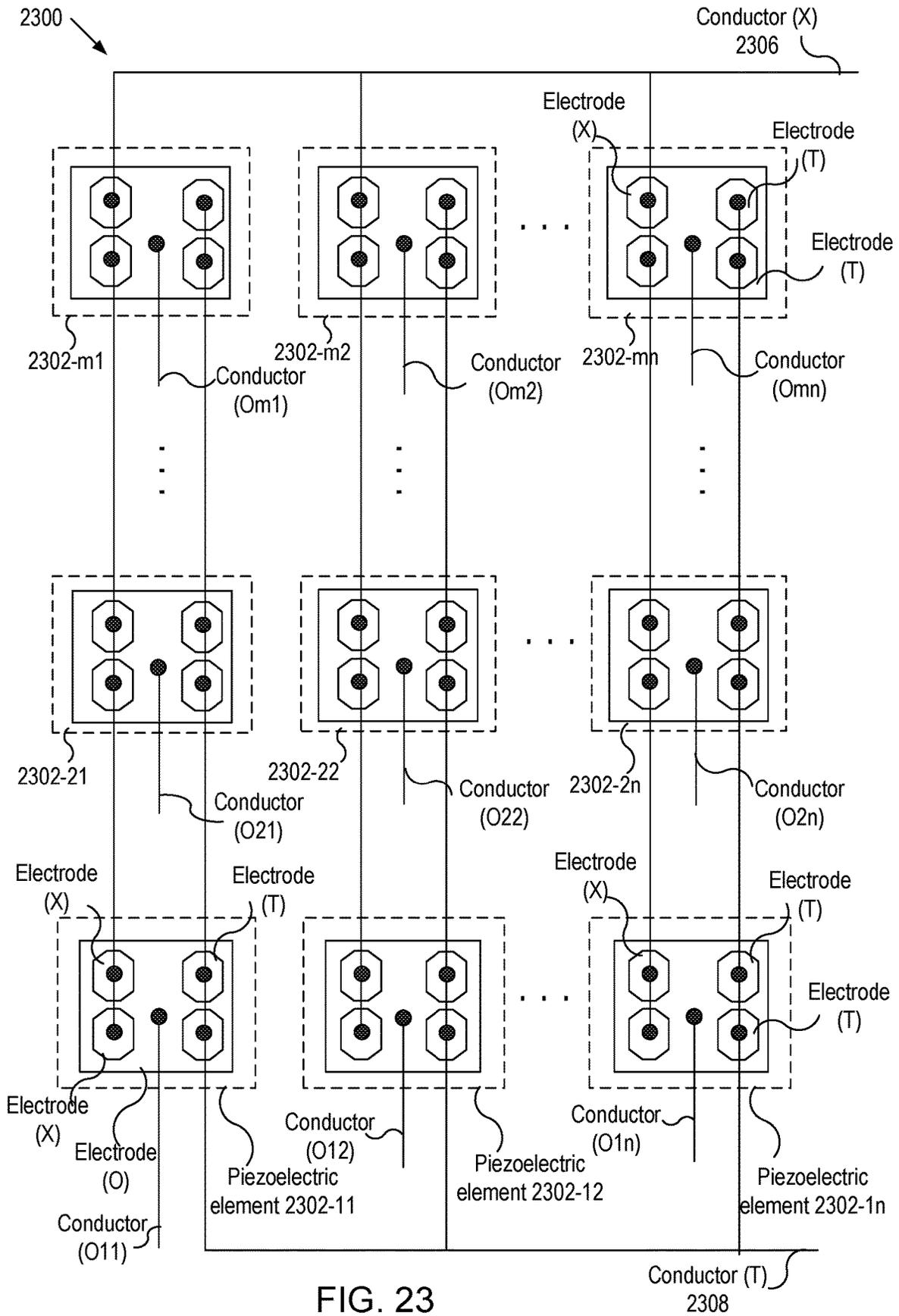


FIG. 22



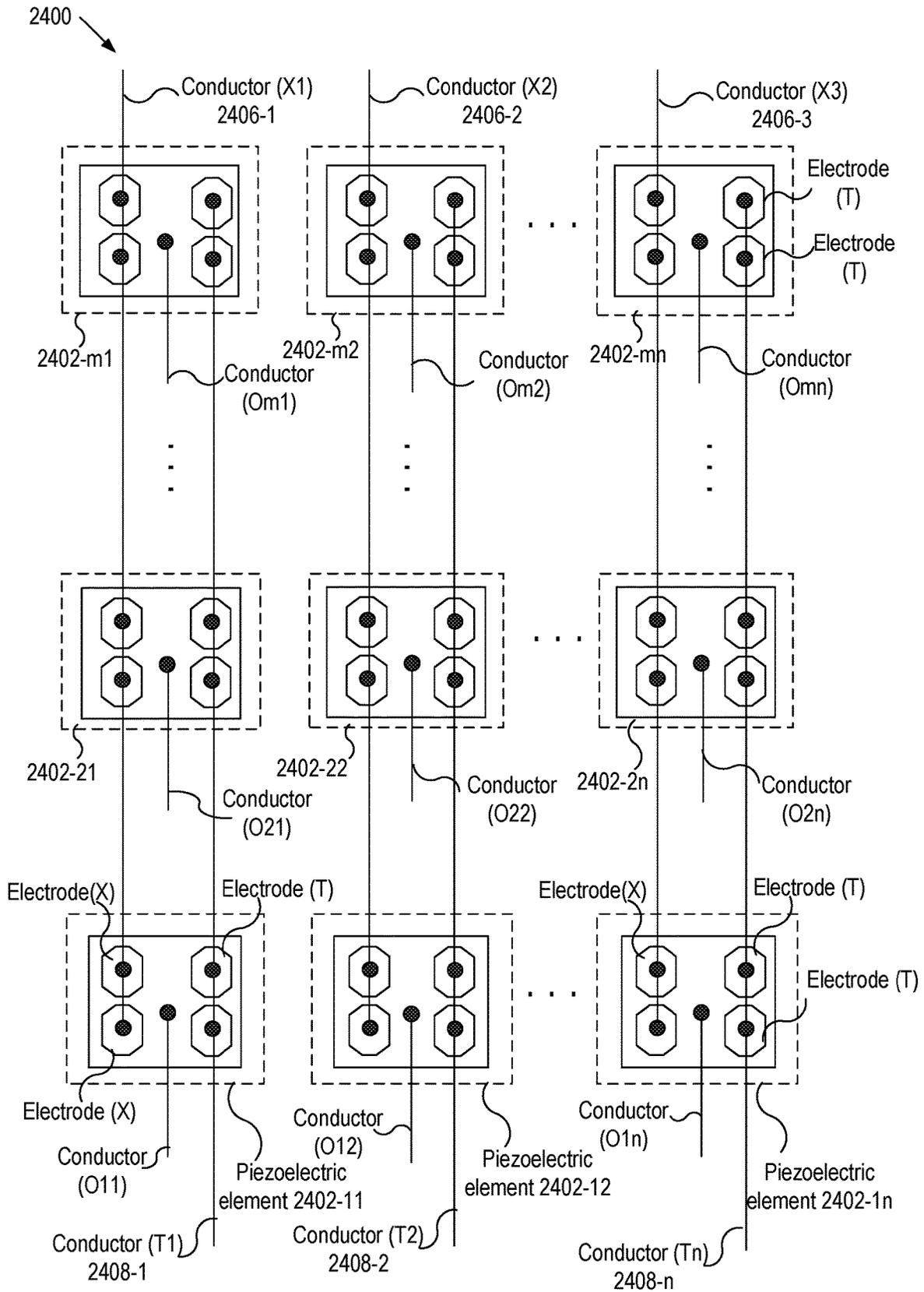


FIG. 24

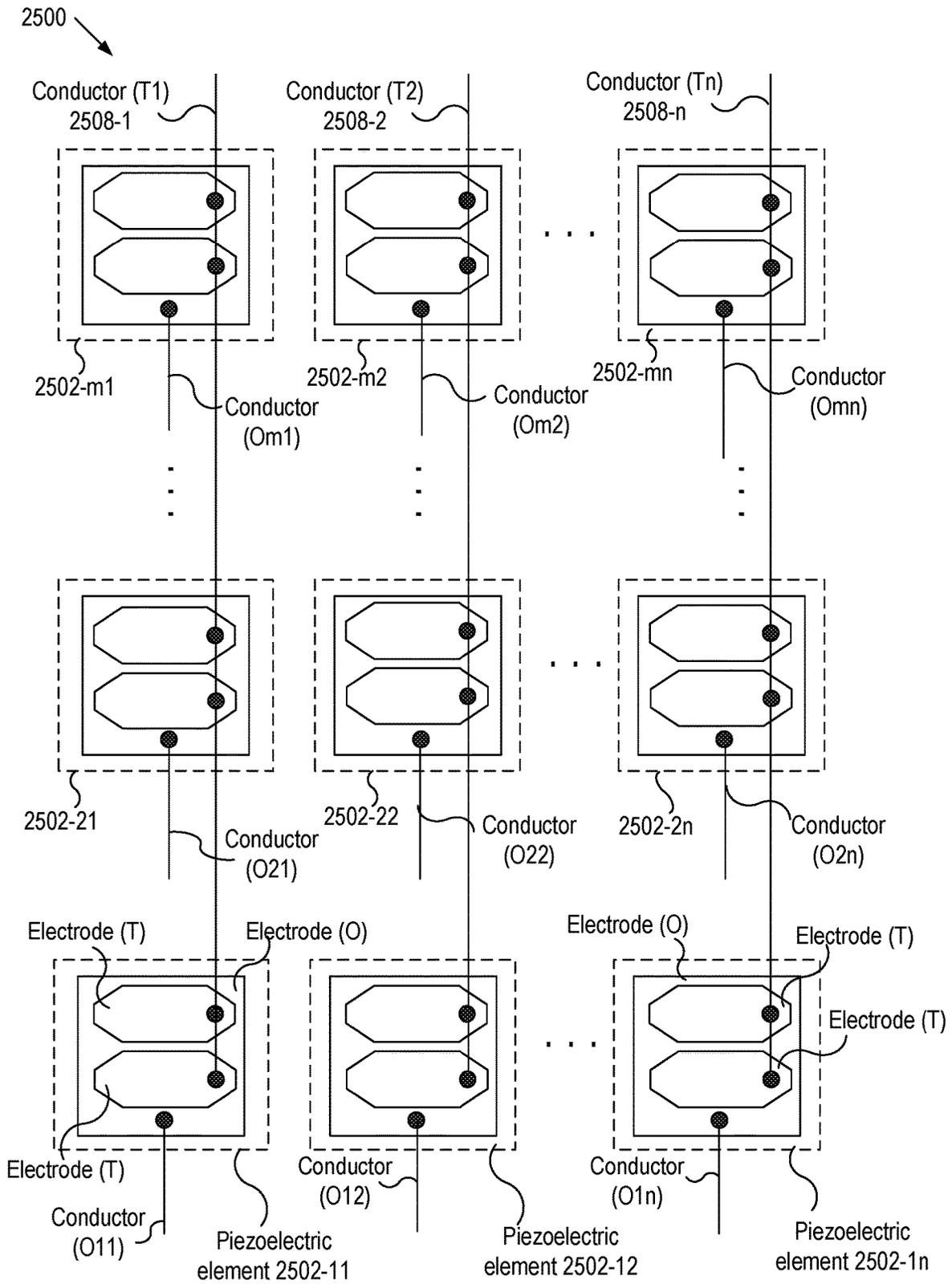


FIG. 25

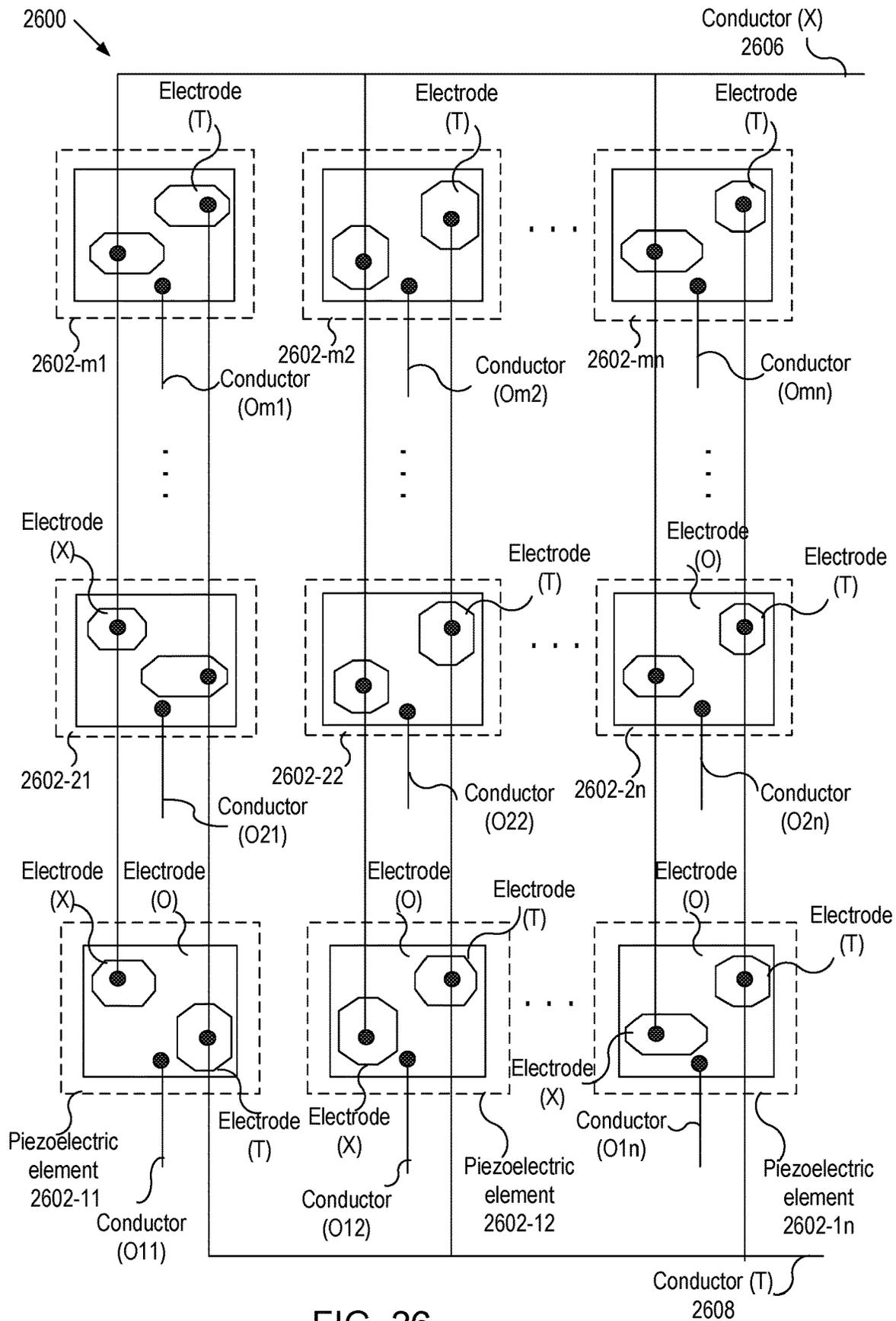


FIG. 26

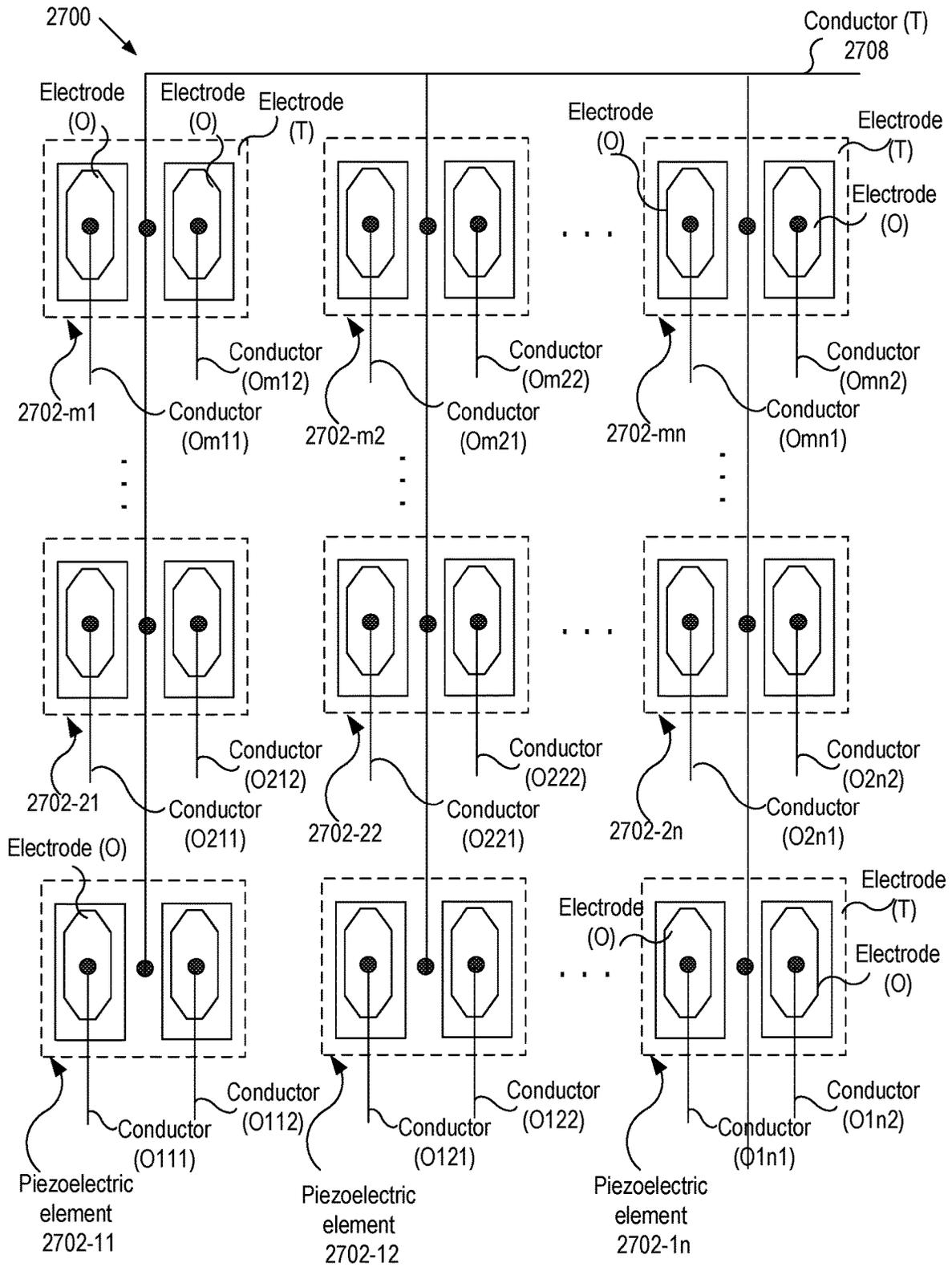


FIG. 27

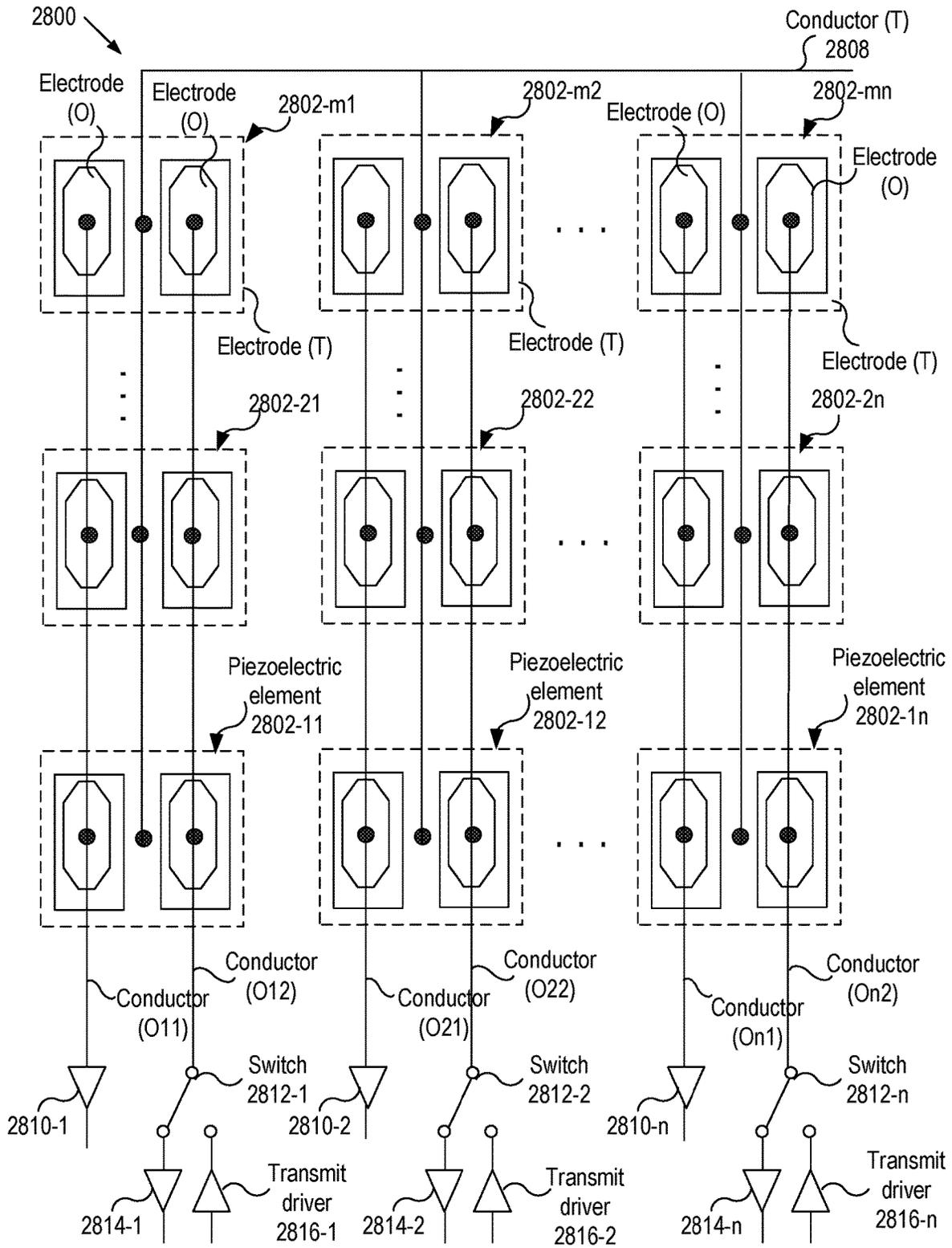


FIG. 28

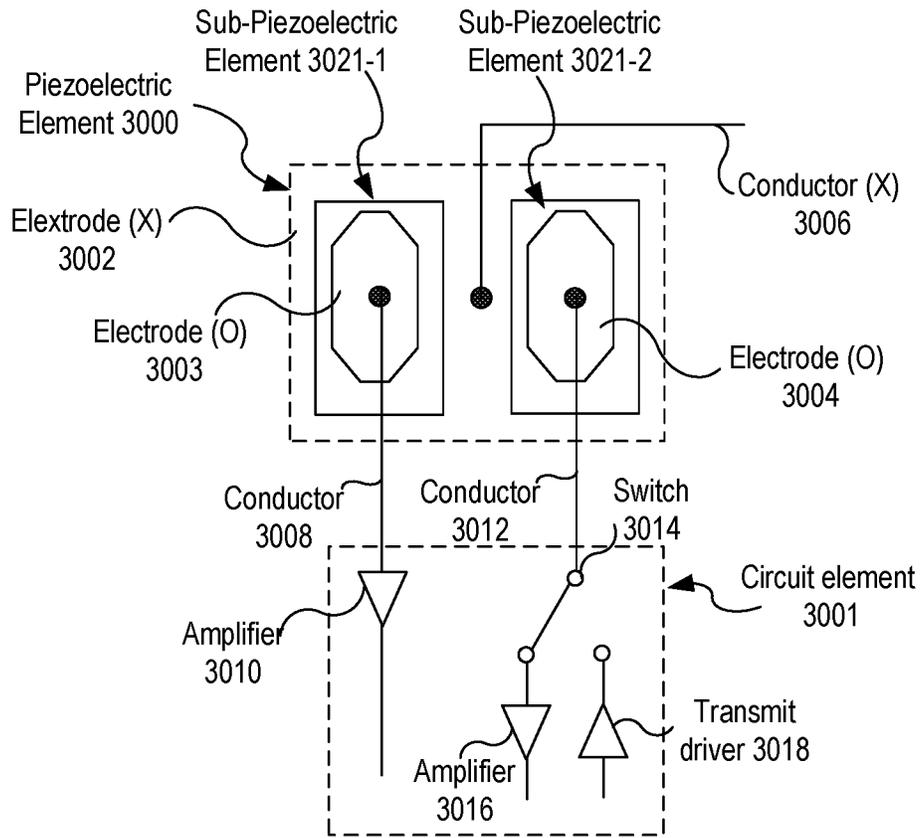


FIG. 30

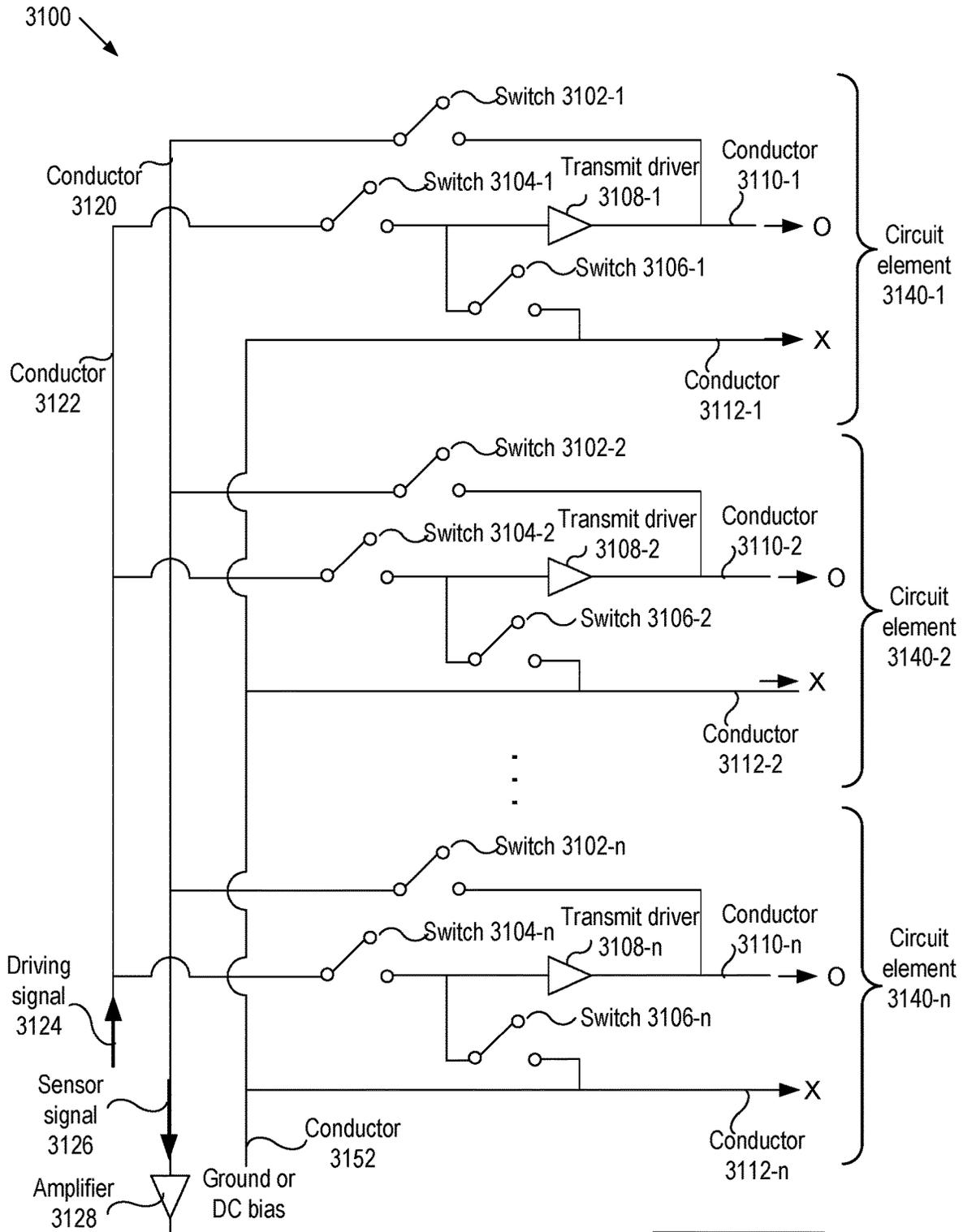


FIG. 31

Control unit
3150

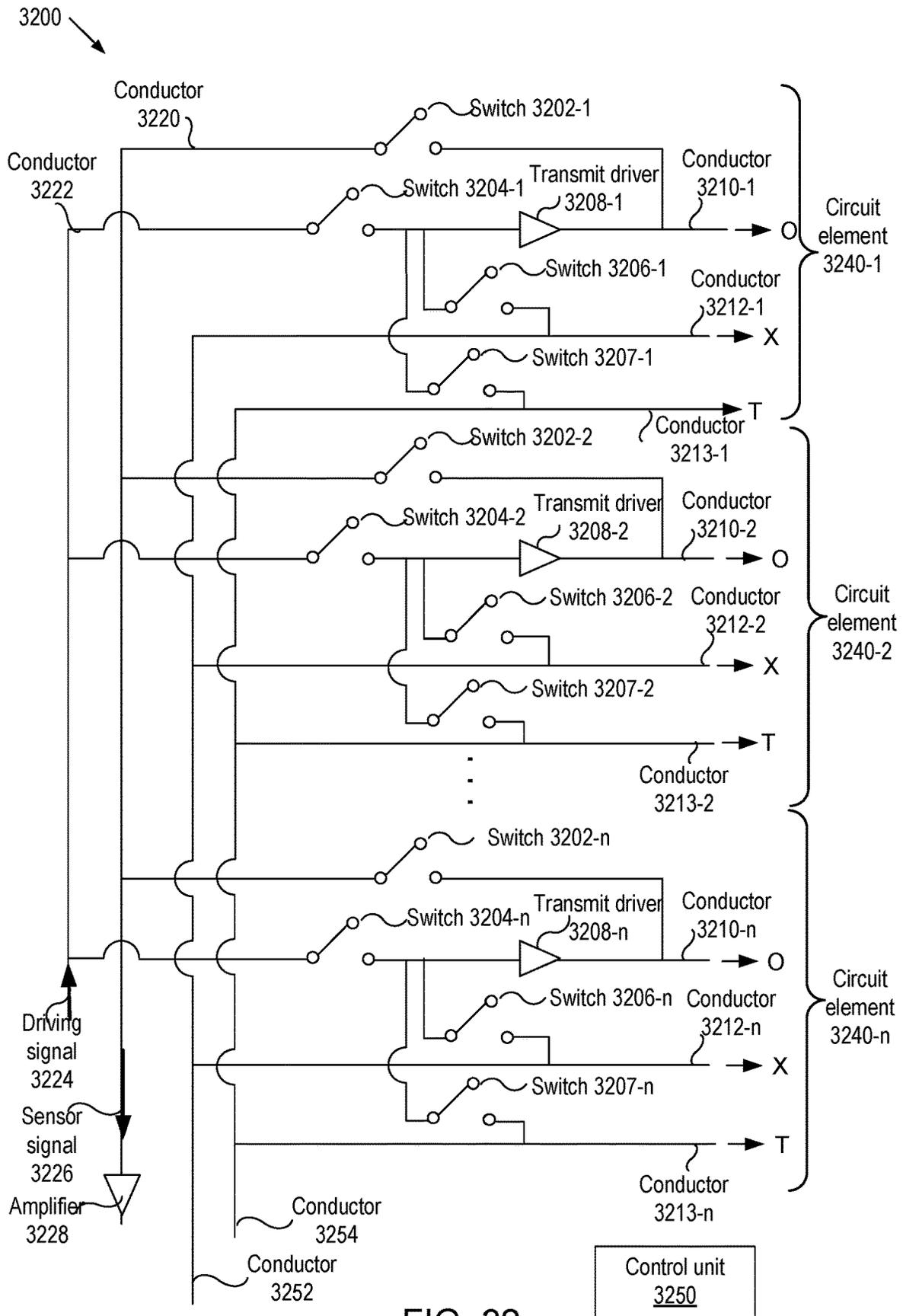


FIG. 32

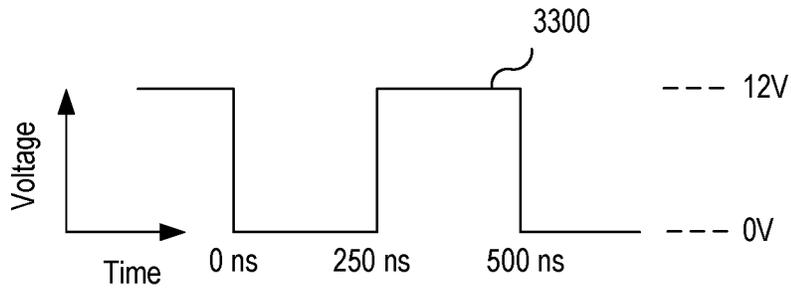


FIG. 33

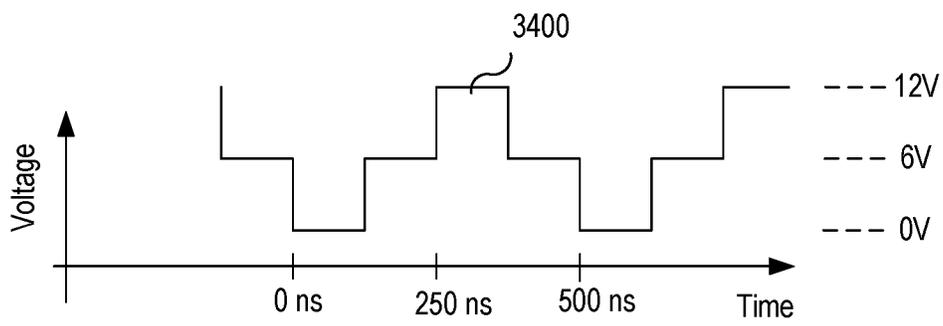


FIG. 34

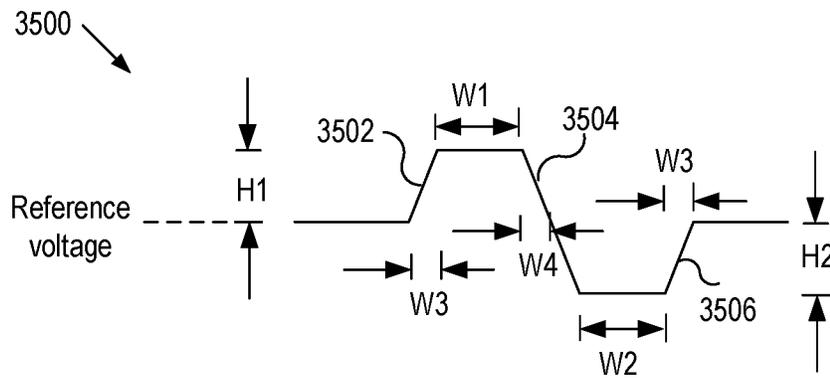


FIG. 35

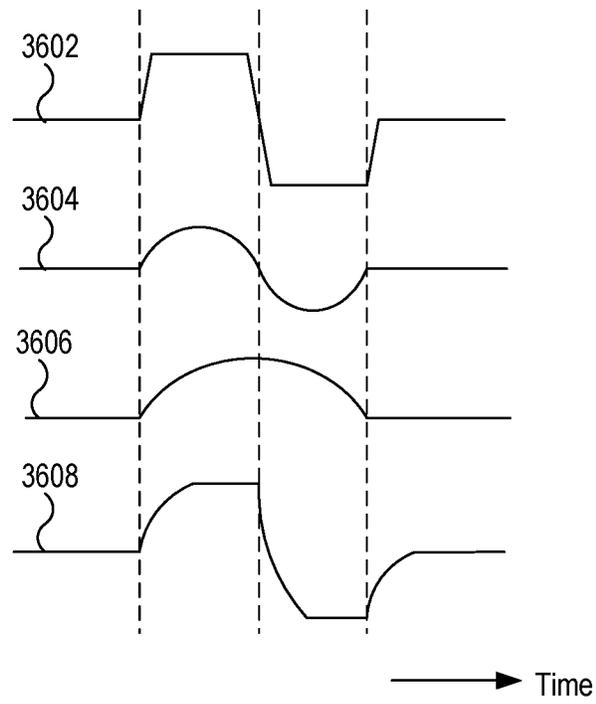


FIG. 36

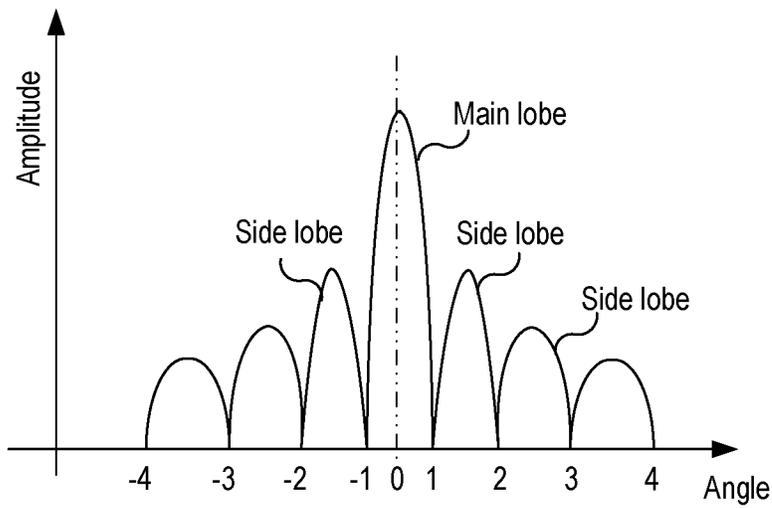


FIG. 37A

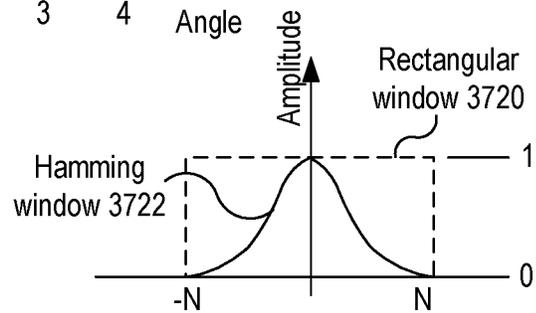


FIG. 37B

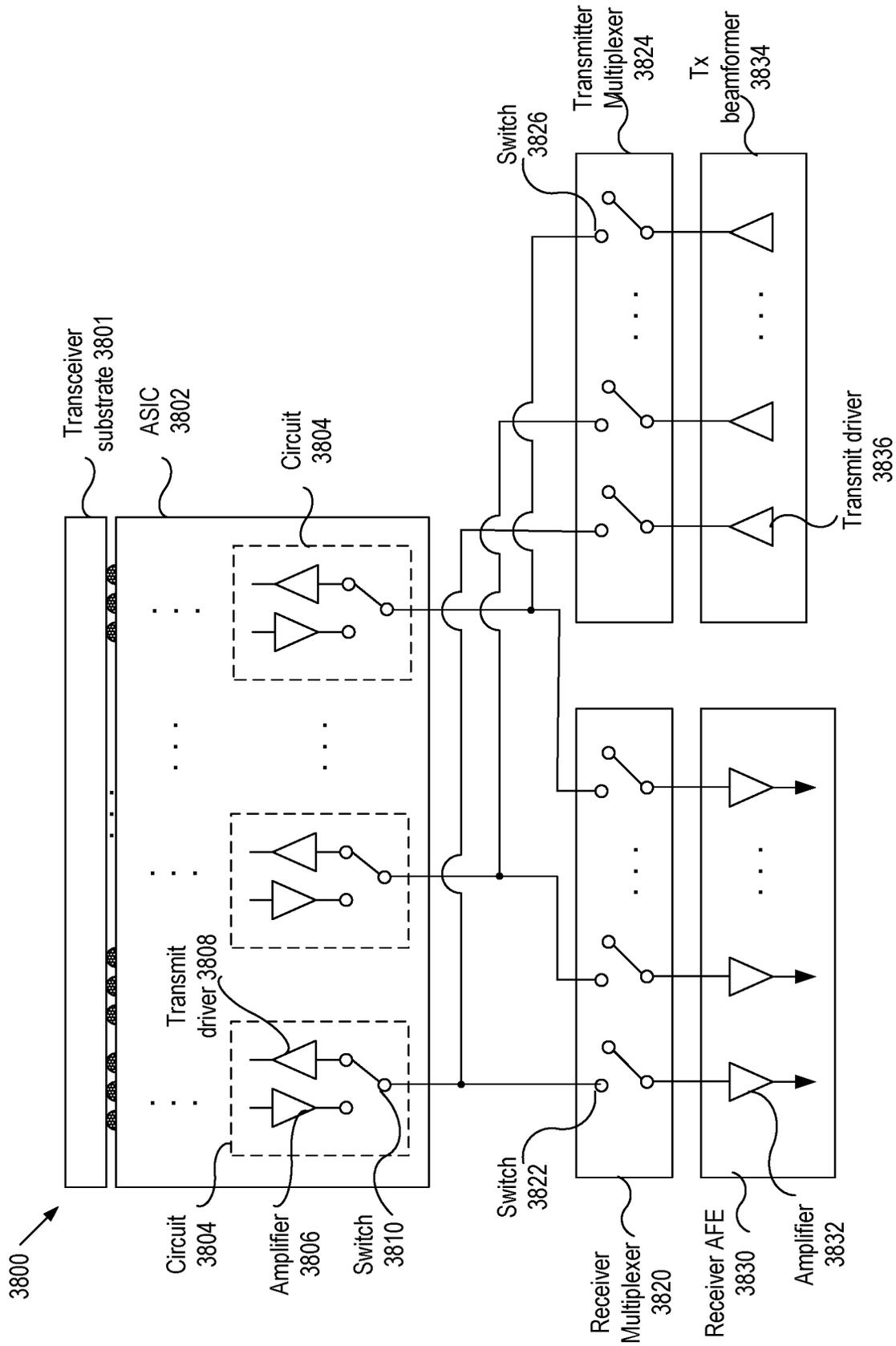


FIG. 38

LOW VOLTAGE, LOW POWER MEMS TRANSDUCER WITH DIRECT INTERCONNECT CAPABILITY

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Nos. 62/429,832, filed on Dec. 4, 2016, entitled "A Configurable Ultrasonic Line Imager," 62/429,833, filed on Dec. 4, 2016, entitled "Low Voltage, Low Power MEMS Transducer with Direct Interconnect," and 62/433,782, filed on Dec. 13, 2016, entitled "Micromachined Transceiver Array," which are hereby incorporated by reference in their entirety.

BACKGROUND

A. Technical Field

The present invention relates to imaging devices, and more particularly, to imaging devices having configurable ultrasonic line imagers.

B. Background of the Invention

A non-intrusive imaging system/probe for imaging internal tissue, bones, blood flow or organs of human or animal body and displaying the images requires transmission of a signal into the body and receiving an emitted or reflected signal from the body part being imaged. Typically, transducers that are used in an imaging system are referred to as transceivers and some of the transceivers are based on photo-acoustic or ultrasonic effects. In general, the transceivers are used for imaging, but are not necessarily limited to imaging. For example, the transceivers can be used in medical imaging, flow measurements in pipes, speaker and microphone arrays, lithotripsy, localized tissue heating for therapeutics or highly intensive focused ultrasound (HIFU) for surgery.

The conventional transducers built from bulk piezoelectric (PZT) material typically require very high voltage pulses to generate transmission signals, typically 100 V or more. This high voltage results in high power dissipation, since the power consumption/dissipation in the transducers is proportional to the square of the drive voltage. There is also a limit on how hot the surface of the probe could be and this limits how much power could be consumed in the probe, since the consumed power is proportional to the heat generated by the probe. In the conventional systems, the heat generation has necessitated cooling arrangements for some probes, increasing the manufacturing costs and weights of the probes. In general, the weight of the conventional probe is also an issue, since a large number of sonographers, who use these probes, are known to suffer from muscular injuries.

The conventional ultrasound probes in use for medical imaging typically use PZT material or other piezo ceramic and polymer composites. Probes typically house the transducers and some other electronics with means to cause an image to be displayed on a display unit. To fabricate the conventional bulk PZT elements for the transducers, one can simply cut a thick piezoelectric material slab into large rectangular shaped PZT elements. These rectangular shaped PZT elements are very expensive to build, since the manufacturing process involves precisely cutting of the rectangular shaped thick PZT or ceramic material and mounting on substrates with precise spacing. Further, the impedance of

the transducers is much higher than the impedance of the transmit/receive electronics for the transducers.

In the conventional systems, the transmit/receive electronics for the transducers often are located far away from the probe, requiring micro-coax cables between the transducers and electronics. In general, the cables need to have a precise length for delay and impedance matching, and, quite often, additional impedance matching networks are required for efficient connection of the transducers through the cables to the electronics.

Advances in micro-machining technologies allow sensors and actuators, such as capacitive micromachined ultrasound transducers (cMUTs) and piezoelectric micromachined ultrasound transducers (pMUTs), to be efficiently formed on a substrate. Compared to the conventional transducers having bulky piezoelectric material, pMUTs are less bulky and cheaper to manufacture while they have simpler and higher performance interconnection between electronics and transducers, provide greater flexibility in the operational frequency, and potential to generate higher quality images.

Although the basic concepts for these transducers have been disclosed in the early 1990's, commercial implementation of these concepts has met with a number of challenges. For instance, the conventional cMUT sensors are particularly prone to failure or drift in performance due to the charge build-up during the high voltage operation, difficulty with generating high enough acoustic pressure at lower frequencies and are inherently nonlinear. The conventional pMUTs have been a promising alternative but have issues related to transmission and receive inefficiencies, still required relatively high operating voltages and had limited bandwidth. As such, there is a need for pMUTs that have an enhanced efficiency, that can operate at lower voltages and exhibit high bandwidth.

SUMMARY OF THE DISCLOSURE

In embodiments, a transceiver includes: a substrate; a membrane suspending from the substrate; a bottom electrode disposed on the membrane; a piezoelectric layer disposed on the bottom electrode; first and second top electrodes disposed on the piezoelectric layer, the first top electrode being electrically separated from the second top electrode; and the piezoelectric layer including a first portion located under the first top electrode and poled in a first direction and a second portion located under the second top electrode and poled in a second direction that is opposite to the first direction.

In embodiments, a transceiver includes: a transceiver substrate and an ASIC chip. The transceiver substrate includes: a substrate; at least one membrane disposed on the substrate; and a plurality of piezoelectric elements disposed on the at least one membrane, each of the plurality of piezoelectric elements including; a bottom electrode; a piezoelectric layer disposed on the bottom electrode; first and second top electrodes disposed on the piezoelectric layer, the first top electrode being electrically and spatially separated from the second top electrode; and the piezoelectric layer including a first portion located under the first top electrode and poled in a first direction and a second portion located under the second top electrode and poled in a second direction that is opposite to the first direction. The ASIC chip is electrically coupled to the transceiver substrate by a three dimensional interconnection mechanism and includes: at least one circuit for controlling one or more of the plurality

of piezoelectric elements; and a control unit electrically coupled to the at least one circuit and controlling the at least one circuit.

In embodiments, an imaging system includes first and second imaging device. Each of the first and second imaging device includes: a substrate; at least one membrane disposed on the substrate; and a plurality of piezoelectric elements disposed on the at least one membrane. Each of the plurality of piezoelectric elements includes; a bottom electrode; a piezoelectric layer disposed on the bottom electrode; first and second top electrodes disposed on the piezoelectric layer, the first top electrode being electrically and spatially separated from the second top electrode; and the piezoelectric layer including a first portion located under the first top electrode and poled in a first direction and a second portion located under the second top electrode and poled in a second direction that is opposite to the first direction. The first imaging device transmits pressure waves toward a target to be imaged and wherein the second imaging device is located at a different location from the first imaging device and receives pressure waves reflected from the target.

BRIEF DESCRIPTION OF THE DRAWINGS

References will be made to embodiments of the invention, examples of which may be illustrated in the accompanying figures. These figures are intended to be illustrative, not limiting. Although the invention is generally described in the context of these embodiments, it should be understood that it is not intended to limit the scope of the invention to these particular embodiments.

Figure (or "FIG.") 1 shows a schematic diagram of an imaging system according to embodiments of the present disclosure.

FIG. 2 shows a schematic diagram of an ultrasonic imager according to embodiments of the present disclosure. FIG. 2A shows a schematic diagram of an ultrasonic imager according to embodiments of the present disclosure.

FIG. 3A shows a side views of an exemplary transceiver array according to embodiments of the present disclosure.

FIG. 3B shows a top view of a transceiver tile according to embodiments of the present disclosure.

FIG. 4-8 show steps for fabricating an exemplary piezoelectric element according to embodiments of the present disclosure.

FIG. 9 shows a schematic diagram of a piezoelectric element according to embodiments of the present disclosure.

FIG. 10A shows a schematic diagram of a piezoelectric element according to embodiments of the present disclosure.

FIG. 10B shows a symbolic representation of the piezoelectric element in FIG. 10A.

FIG. 10C shows a schematic cross sectional view of an exemplary piezoelectric element according to embodiments of the present disclosure.

FIG. 10D shows a schematic diagram of a piezoelectric element according to embodiments of the present disclosure.

FIG. 10E shows a schematic diagram of a piezoelectric element according to embodiments of the present disclosure.

FIG. 10F shows a schematic diagram of a piezoelectric element according to embodiments of the present disclosure.

FIG. 10G shows a bottom view of the piezoelectric element in FIG. 10F according to embodiments of the present disclosure.

FIG. 10H shows a cross sectional view of the piezoelectric element in FIG. 10F according to embodiments of the present disclosure.

FIG. 11 shows a schematic diagram of a piezoelectric element according to embodiments of the present disclosure.

FIG. 12-16 shows steps for fabricating an exemplary piezoelectric element according to embodiments of the present disclosure.

FIG. 17A shows dipole orientations of a piezoelectric material before, during and after a poling process according to embodiments of the present disclosure.

FIG. 17B shows a flow chart of an illustrative process for poling a piezoelectric layer according to embodiments of the present disclosure.

FIG. 18A shows a schematic diagram of an imaging assembly according to embodiments of the present disclosure.

FIG. 18B shows a schematic diagram of an imaging assembly according to embodiments of the present disclosure.

FIG. 19A-1 shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 19A-2 shows a side view of an imaging assembly according to embodiments of the present disclosure.

FIG. 19B-1 shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 19B-2 shows a side view of an imaging assembly according to embodiments of the present disclosure.

FIG. 19C shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 19D shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 19E shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 19F shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 19G shows a top view of a transceiver substrate and an ASIC chip according to embodiments of the present disclosure.

FIG. 20 illustrates a schematic diagram of an array of piezoelectric elements capable of performing two and three dimensional imaging according to embodiments of the present disclosure.

FIG. 21 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 22 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 23 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 24 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 25 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 26 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 27 illustrates a schematic diagram of an array of piezoelectric elements according to embodiments of the present disclosure.

FIG. 28 illustrates a schematic diagram of an imaging system according to embodiments of the present disclosure.

FIG. 29 illustrates a schematic diagram of an imaging system according to embodiments of the present disclosure.

FIG. 30 shows an embodiment of a piezoelectric element coupled to a circuit element according to embodiments of the present disclosure.

FIG. 31 shows a circuit for controlling multiple piezoelectric element according to embodiments of the present disclosure.

FIG. 32 shows a circuit for controlling multiple piezoelectric element according to embodiments of the present disclosure.

FIG. 33 shows a transmit drive signal waveform according to embodiments of the present disclosure.

FIG. 34 shows a transmit drive signal waveform according to embodiments of the present disclosure.

FIG. 35 shows a transmit drive signal waveform according to embodiments of the present disclosure.

FIG. 36 shows input/output signals of various circuits in an imaging assembly according to embodiments of the present disclosure.

FIG. 37A shows a plot of the amplitude of a transmit pressure wave as a function of angle according to embodiments of the present disclosure.

FIG. 37B shows windows for apodization process according to embodiments of the present disclosure.

FIG. 38 shows a schematic diagram of an imaging assembly according to embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the following description, for purposes of explanation, specific details are set forth in order to provide an understanding of the disclosure. It will be apparent, however, to one skilled in the art that the disclosure can be practiced without these details. Furthermore, one skilled in the art will recognize that embodiments of the present disclosure, described below, may be implemented in a variety of ways, such as a process, an apparatus, a system, a device, or a method on a tangible computer-readable medium.

One skilled in the art shall recognize: (1) that certain fabrication steps may optionally be performed; (2) that steps may not be limited to the specific order set forth herein; and (3) that certain steps may be performed in different orders, including being done contemporaneously.

Elements/components shown in diagrams are illustrative of exemplary embodiments of the disclosure and are meant to avoid obscuring the disclosure. Reference in the specification to “one embodiment,” “preferred embodiment,” “an embodiment,” or “embodiments” means that a particular feature, structure, characteristic, or function described in connection with the embodiment is included in at least one embodiment of the disclosure and may be in more than one embodiment. The appearances of the phrases “in one embodiment,” “in an embodiment,” or “in embodiments” in various places in the specification are not necessarily all referring to the same embodiment or embodiments. The terms “include,” “including,” “comprise,” and “comprising” shall be understood to be open terms and any lists that follow are examples and not meant to be limited to the listed items. Any headings used herein are for organizational purposes only and shall not be used to limit the scope of the description or the claims. Furthermore, the use of certain terms in various places in the specification is for illustration and should not be construed as limiting.

In embodiments, the pMUT transducers and transducer assemblies may be used for generating images of internal organs of a human/animal body as well as other therapeutic applications where ultrasonic beams are used to heat tissue for healing or focus high power ultrasonic beams for micro surgery. In embodiments, the piezoelectric elements may also be used for tomography applications.

In embodiments, the manufacturing cost of pMUTs may be reduced by applying modern semiconductor and wafer processing techniques. In embodiments, thin film piezoelectric layer may be spun on or sputtered onto semiconductor wafers and later patterned to create piezoelectric sensors that each have two or more electrodes. In embodiment, each piezoelectric element may be designed to have the ability to emit or receive signals at a certain frequency, known as center frequency, as well as the second and/or additional frequencies. Hereinafter, the terms piezoelectric element, pMUT, transceiver, and pixel are used interchangeably.

FIG. 1 shows a schematic diagram of an imaging system **100** according to embodiments of the present disclosure. As depicted, the system **100** may include: an imager **120** that generates and transmits pressure waves **122** toward an internal organ **112**, such as heart, in a transmit mode/process; and a device **102** that sends and receives signals to the imager through a communication channel **130**. In embodiments, the internal organ **112** may reflect a portion of the pressure waves **122** toward the imager **120**, and the imager **120** may capture the reflected pressure waves and generate electrical signals in a receive mode/process. The imager **120** may communicate electrical signals to the device **102** and the device **102** may display images of the organ or target on a display/screen **104** using the electrical signals.

In embodiment, the imager **120** may be used to perform one dimensional imaging, also known as A-Scan, two dimensional imaging, also known as B scan, three dimensional imaging, also sometimes referred to as C scan, and Doppler imaging. Also, the imager may be switched to various imaging modes under program control.

In embodiments, the imager **120** may be used to get an image of internal organs of an animal, too. The imager **120** may also be used to determine direction and velocity of blood flow in arteries and veins as in Doppler mode imaging and also measure tissue stiffness. In embodiments, the pressure wave **122** may be acoustic, ultrasonic, or photo-acoustic waves that can travel through the human/animal body and be reflected by the internal organs, tissue or arteries and veins.

In embodiments, the imager **120** may be a portable device and communicate signals through the communication channel **130**, either wirelessly (using a protocol, such as 802.11 protocol) or via a cable (such as USB2, USB3, USB3.1, and USB-C), with the device **102**. In embodiments, the device **102** may be a mobile device, such as cell phone or iPad, or a stationary computing device that can display images to a user.

In embodiments, an imager may be configured to simultaneously transmit and receive ultrasonic waveforms. Certain piezoelectric elements may be configured to send pressure waves toward the target organ being imaged while other piezoelectric elements may receive the pressure waves reflected from the target organ and develop electrical charges in response to the received waves.

FIG. 2 shows a schematic diagram of the imager **120** according to embodiments of the present disclosure. In embodiments, the imager **120** may be an ultrasonic imager. As depicted in FIG. 2, the imager **120** may include: a transceiver tile(s) **210** for transmitting and receiving pres-

sure waves; a coating layer **212** that operates as a lens for steering the propagation direction of and/or focusing the pressure waves and also functions as an impedance interface between the transceiver tile and the human body **110**; a control unit **202**, such as ASIC chip (or, shortly ASIC), for controlling the transceiver tile(s) **210** and coupled to the transducer tile **210** by bumps; Field Programmable Gate Arrays (FPGAs) **214** for controlling the components of the imager **120**; a circuit(s) **215**, such as Analogue Front End (AFE), for processing/conditioning signals; an acoustic absorber layer **203** for absorbing waves that are generated by the transducer tiles **210** and propagate toward the circuit **215**; a communication unit **208** for communicating data with an external device, such as the device **102**, through one or more ports **216**; a memory **218** for storing data; a battery **206** for providing electrical power to the components of the imager; and optionally a display **217** for displaying images of the target organs.

In embodiments, the device **102** may have a display/screen. In such a case, the display may not be included in the imager **120**. In embodiments, the imager **120** may receive electrical power from the device **102** through one of the ports **230**. In such a case, the imager **120** may not include the battery **206**. It is noted that one or more of the components of the imager **120** may be combined into one integral electrical element. Likewise, each component of the imager **120** may be implemented in one or more electrical elements.

In embodiments, the user may apply gel on the skin of the human body **110** before the body **110** makes a direct contact with the coating layer **212** so that the impedance matching at the interface between the coating layer **212** and the human body **110** may be improved, i.e., the loss of the pressure wave **122** at the interface is reduced and the loss of the reflected wave travelling toward the imager **120** is also reduced at the interface. In embodiments, the transceiver tiles **210** may be mounted on a substrate and may be attached to an acoustic absorber layer. This layer absorbs any ultrasonic signals that are emitted in the reverse direction, which may otherwise be reflected and interfere with the quality of the image.

As discussed below, the coating layer **212** may be only a flat matching layer just to maximize transmission of acoustic signals from the transducer to the body and vice versa. In embodiments, the thickness of the coating layer **212** may be a quarter wavelength of the pressure wave generated by the transducer tile(s) **202**. Beam focus in the elevation direction, which is along the direction of the length of the column, is not essential in this case, because it can be electronically implemented in control unit **202**. Even then, the lens may be designed with a focus in some cases. The imager **120** may use the reflected signal to create an image of the organ **112** and results may be displayed on a screen in a variety of format, such as graphs, plots, and statistics shown with or without the images of the organ **112**.

In some embodiments, the control unit **202**, such as ASIC, may be assembled as one unit together with the transceiver tiles. In other embodiments, the control unit **202** may be located outside the imager **120** and electrically coupled to the transceiver tile **210** via a cable **220** (e.g., as shown in FIG. 2A). In some embodiments, the imager **120** may include a housing or enclosure **250** that encloses the components **202-215** and a heat dissipation mechanism for dissipating heat energy generated by the components as shown in FIG. 2A. In other embodiments, for example, where the control unit **202** is located outside the imager **120**, a second housing or enclosure **251** may be provided to

enclose the control unit **202** while the other components **203-215** are enclosed by the first housing or enclosure **250**.

FIG. 3A shows a schematic diagram of an exemplary transceiver array having three transceiver tiles **210** according to embodiments of the present disclosure. The tiles may be on a planar surface or on a curved surface. FIG. 3B shows a top view of the transceiver tile **210** that includes one or more piezoelectric elements **302** according to embodiments of the present disclosure. As depicted, the transceiver tile **210** may include a transceiver substrate **304** and one or more piezoelectric elements **302** arranged on the transceiver substrate **304**.

Unlike the conventional systems that use bulk piezoelectric elements, in embodiments, the pMUT array **302** may be formed on a wafer and the wafer may be diced to form multiple transceiver tiles **210**. This process may reduce the manufacturing cost since the transceiver tiles **210** may be fabricated in high volume and at low cost. In embodiments, the diameter of the wafer may range 6-12 inches and many pMUT arrays may be batch manufactured. Further, in embodiments, as discussed in conjunction with FIGS. 18 and 19, the integrated circuits for controlling the pMUT array **302** may be formed in an ASIC chip so that the pMUT array **302** may be connected to the matching integrated circuits in close proximity, preferably within 25 μm -100 μm . For example, the transceiver tile **210** may have 1024 pMUT elements **302** and be connected to a matching ASIC chip that has the appropriate number of circuits for driving the 1024 pMUT elements **302**.

In embodiments, each piezoelectric element **302** may have any suitable shape such as, square, rectangle, and circle, so on. In embodiments, two or more piezoelectric elements may be connected to form a larger pixel element. As depicted in FIG. 3B, when building an imager, it is desirable to have a two dimensional array of piezoelectric element **302**, arranged in orthogonal directions. In embodiments, to create a line element, a column of N piezoelectric elements **302** may be connected electrically in parallel. Then, this line element may provide transmission and reception of ultrasonic signals similar to those achieved by a continuous piezoelectric element that is almost N times longer than each element. This line element may be called a column or line or line element interchangeably. It is understood that tiles may be arranged in other shape such as circular, or other shapes. In embodiments, one or more temperature sensors **320** may be installed in the transducer tile **210** to measure the temperature of the tile **210**. It is noted that the imager **120** may include one or more temperature sensors for measuring temperatures at various locations of the imager **120**.

To mimic a line element of the conventional designs, the shape of a piezoelectric element of a given width may need to be very tall. For example, a line element of a conventional design may be 280 μm in width and 8000 μm tall, while the thickness may be 100 μm . However, on the transceiver tile **210**, it is advantageous to design a line element using a plurality of identical piezoelectric elements **302**, where each element may have its characteristic center frequency. In embodiments, when a plurality of the piezoelectric elements **302** are connected together, the composite structure (i.e. the line element) may act as one line element with a center frequency that consists of the center frequencies of all the element pixels. In modern semiconductor processes, these center frequencies match well to each other and have a very small deviation from the center frequency of the line element. It is also possible to mix several pixels of somewhat

different center frequencies to create a wide bandwidth line compared to lines using only one central frequency.

In embodiments, the piezoelectric elements **302** have a suspended membrane associated with them that vibrates at a center frequency when exposed to stimulus at that frequency and behave like resonators. There is a selectivity associated with these resonators, known as a Q factor. In embodiments, for ultrasound imagers, Q may be usually designed to be low (close 1 or thereabouts) and achieved by a combination of design of the pixels and loading applied to the pixels in actual use. In embodiments, the loading may be provided by application of a layer of RTV or other material to the top face of the piezoelectric elements, where the loading may facilitate closer impedance matching between the transducer surface emitting and receiving the pressure waves and the human body part being imaged. In embodiments, the low Q and the well matched center frequency may allow the line element to essentially act like a line imaging element with substantially one center frequency. In embodiments, loading may also include a matching layer below the transducers, where the emitted waveform is absorbed by an acoustic absorber.

In embodiments, for instance, each piezoelectric element **302** may be spaced 250 μm from each other center to center. Further to simplify, say they are square in shape. Now, let's say, to mimic a conventional line element, a column of the piezoelectric elements **302** may be connected to each other. For example, 24 piezoelectric elements **302** in a column may create a line element of roughly 6 mm in elevation, with each element being 0.25 mm in width. In embodiments, this connection may be achieved at wafer level using a metal interconnect layer.

It is noted that the transceiver tile **210** may include one or more membranes that suspend from the substrate and the piezoelectric elements **302** may be disposed on the membranes. In embodiments, as described below in conjunction with FIGS. 4-8, a membrane may be disposed under each of the piezoelectric elements **302**. In embodiments, more than one piezoelectric elements may be disposed on one membrane **309**. In embodiments, more than one membrane may be disposed under one of the piezoelectric elements **302**. More information on the arrangement of piezoelectric elements on a membrane may be found in a copending U.S. patent application Ser. No. 15/820,319, entitled "Imaging devices having piezoelectric transducers," filed on Nov. 21, 2017, which is herein incorporated by reference in its entirety.

For the conventional bulk piezoelectric elements, the voltage potential across the top and bottom electrodes ranges 100V~200V. For the conventional pMUTs, the voltage potential across the top and bottom electrodes is about 30V. In embodiments, in order to reduce this voltage further, the piezoelectric elements **302** may include a scaled down thin piezoelectric layer, and the piezoelectric layer may have a thickness in the order of 2 μm or less. FIGS. 4-8 show steps for fabricating an exemplary piezoelectric element according to embodiments of the present disclosure. FIG. 4 shows a top view of a membrane **406** disposed on a substrate **402** and FIG. 5 shows a cross sectional view of the membrane and substrate, taken along the line 4-4 according to embodiments of the present disclosure. (In embodiments, the substrate **402** may correspond to the transceiver substrate **304** in FIG. 3B.) As depicted, in embodiments, a membrane layer **404** may be deposited on the substrate **402** and a cavity **408** may be formed to remove a portion of the substrate **402**, to thereby form the membrane **406** that may vibrate relative to the substrate **402** in the vertical direction. In embodiment,

the cavity **408** may be formed by conventional wafer processing techniques, such as etching. In embodiments, the substrate **402** may be formed of the same material as the membrane layer **404**. In alternative embodiments, the substrate **402** may be formed of a different material from the membrane layer **404**. It is noted that the cavity **408** may be formed after the other components, such as top conductor (**812** in FIG. 8), of the piezoelectric element is formed.

In embodiments, the membrane **406** has a circular projection area. However, it should be apparent to those of ordinary skill in the art that the membrane **406** may have other suitable geometrical shape.

FIG. 6 shows a top view of a bottom electrode **602** disposed on the membrane layer **404** and arranged over the membrane **406** according to embodiments of the present disclosure. FIG. 7 shows a top view of a piezoelectric layer **706** disposed on the bottom electrode **602** according to embodiments of the present disclosure. In embodiments, the piezoelectric layer **706** may have the similar projection area as the bottom electrode **602** so that the piezoelectric layer **706** may cover the entire portion of the bottom electrode **602**.

FIG. 8 shows a top view of a piezoelectric element according to embodiments of the present disclosure. As depicted, a top electrode **808** may be disposed on the piezoelectric layer **706** and arranged over the membrane **406**. In embodiments, a conductor **812** may be disposed on and electrically coupled to the top electrode **808**, while conductors **810** and **811** may reach the bottom electrode **602** through one or more vias **814**. In embodiments, the top electrode **808**, the piezoelectric layer **706** and the bottom electrode **602** may form a two terminal piezoelectric element and the membrane **406** may vibrate when an electrical voltage is applied across the top and bottom electrodes. In embodiments, electrical charge may be developed in the top and bottom electrodes when the membrane is deformed by a pressure wave during a receive mode/process.

FIG. 9 shows a schematic diagram of a piezoelectric element **900** according to embodiments of the present disclosure. As depicted, a piezoelectric layer **910** may be disposed between a first electrode (X) **906** and a second electrode (O) **904**. In embodiments, the first electrode (X) **906** may be connected to a ground or a DC bias via the conductor (X) **908** and the second electrode (O) **904** may be connected to an electrical circuit (not shown in FIG. 9) through a signal conductor (O) **902**. In embodiments, the piezoelectric element **800** in FIG. 8 is an exemplary implementation of the piezoelectric element **900** and the piezoelectric element **900** may be disposed on a membrane layer (such as **404** in FIG. 5).

In the conventional piezoelectric elements, the piezoelectric layer is thick, approaching around 100 μm and typically an AC voltage of +100 to -100 V across the piezoelectric layer is required to create an ultrasonic pressure wave of sufficient strength to enable medical imaging. The frequency of this AC drive signal is typically around the resonating frequency of the piezoelectric structure, and typically above 1 MHz for medical imaging applications. In the conventional systems, the power dissipated in driving the piezoelectric element is proportional to $C \cdot V^2$, where C is capacitance of the piezoelectric element and V is the maximum voltage across the piezoelectric layer. Typically, when transmitting pressure waves, multiple piezoelectric lines are driven together with somewhat different phase delays to focus the pressure waves or to steer a propagation direction of the pressure waves. The simultaneous drive of multiple piezoelectric lines causes the temperature at the surface of

the piezoelectric elements to rise. In general, it is highly desirable not to exceed a certain threshold temperature, so as not to injure the subject being imaged. This limits the number of lines that can be driven and the time period for which they can be driven.

In embodiments, the piezoelectric layer **910** is much thinner, approximately 1 to 2 μm thick, compared to the conventional bulk piezoelectric elements. In embodiments, this large reduction in thickness may enable the use of lower voltage drive signals for the piezoelectric element **900**, where the voltage is lowered approximately by the amount by which the thickness of the piezoelectric layer **910** is lowered to maintain the similar electric field strength. For example, in embodiments, the voltage potential across the two electrodes **904** and **906** may range from around 1.8 V to 12.6 V peak to peak. The capacitance of the piezoelectric element **900** may increase due to the reduction in thickness of the piezoelectric layer **910** for similar piezoelectric material. For instance, when the drive voltage is decreased by a factor of 10 while the thickness of the piezoelectric layer **910** is also decreased by a factor of 10, the capacitance increases by a factor of 10 and the power dissipation decreases by a factor of 10. This reduction in power dissipation also reduces heat generation and temperature rise in the piezoelectric element. Thus, in embodiments, using lower drive voltages and thinner piezoelectric layer, compared to the conventional piezoelectric elements, the temperature of the pMUT surface may be lowered. Alternately, in embodiments, for a given temperature, more pMUT elements may be driven simultaneously to illuminate the larger target area, compared to the conventional piezoelectric elements. This may allow faster scanning of the target, especially if multiple emissions are needed to scan the entire portion of the target to form one image. In embodiments, a target area may be scanned with multiple emissions using different steering angles and the obtained image data may be combined to obtain a higher quality image.

Compared to the conventional bulk piezoelectric elements, in embodiments, the ability to drive more piezoelectric elements simultaneously may allow more coverage of the transducer aperture per emission, minimizing the number of emissions needed to cover the entire aperture, thus increasing frame rates. A frame rate measures how many times a target is imaged per minute. It is desirable to image at a high frame rate, especially when tissue motion is involved since the moving tissue may make the image blurry. In embodiments, the imager **120** that operates at a higher frame rate may be able to generate images of enhanced quality, compared to the conventional bulk piezoelectric elements.

In embodiments, image quality may be improved by compounding several frames of images into one resultant lower noise frame. In embodiments, by using low voltage and low power pMUTs with a high frame rate, compared to the conventional bulk piezoelectric elements, for a given rise in the pMUT temperature, this averaging technique may be feasible to enhance the image quality. In embodiments, the synthetic aperture method of ultrasound imaging may be used to allow compounding of images. The various frames of images may also be with different steering angles or from orthogonal steering directions to better view the target.

FIG. **10A** shows a schematic diagram of a piezoelectric element **1000** according to embodiments of the present disclosure. FIG. **10B** shows a symbolic representation of the piezoelectric element **1000** in FIG. **10A**. As depicted, the piezoelectric element **1000** is similar to the piezoelectric element **900**, with the difference that the piezoelectric ele-

ment **1000** has more than two electrodes. More specifically, the piezoelectric element **1000** may include: a top electrode (O) **100**, a first bottom electrode (X) **1006**; a second bottom electrode (T) **1012**; a piezoelectric layer **1010** disposed between the top and bottom electrodes; and three conductors **1002**, **1008** and **1014** that are electrically coupled to the bottom and top electrodes **1004**, **1006** and **1012**, respectively. (Hereinafter, the terms top and bottom merely refer to two opposite sides of the piezoelectric layer, i.e., the top electrode is not necessarily disposed over the bottom electrode.)

While a unimorph piezoelectric element is shown in FIG. **10A** purely for the purpose of illustration, in embodiments, a multilayer piezoelectric element composed of a plurality of piezoelectric sublayers and electrodes can be utilized. In embodiments, the piezoelectric layer **1010** may include at least one of PZT, PZT-N, PMN—Pt, AlN, Sc—AlN, ZnO, PVDF, and LiNiO₃.

FIG. **10C** shows a schematic cross sectional diagram of the piezoelectric element **1000** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1000** may be disposed on a membrane layer **1034** that is supported by a substrate **1030**. In embodiments, a cavity **1032** may be formed in the substrate **1030** to define a membrane. In embodiments, the membrane layer **1034** may be formed by depositing SiO₂ on the substrate **1030**.

In embodiments, the piezoelectric element **1000** may include a piezoelectric layer **1010** and a first electrode (O) **1002** that is electrically connected to a signal conductor (O) **1004**. In embodiments, the signal conductor (O) **1004** may be formed by depositing TiO₂ and metal layers on the membrane layer **1034**. In embodiments, the piezoelectric layer **1010** may be formed by the sputtering technique or by the Sol Gel process.

In embodiments, a second electrode (X) **1006** may be grown above the piezoelectric layer **1010** and electrically connected to a second conductor **1008**. A third electrode (T) **1012** may be also grown above the piezoelectric layer **1010** and disposed adjacent to the second conductor **1012** but electrically isolated from the second conductor (X) **1008**. In embodiments, the second electrode (X) **1006** and third electrode (T) **1012** may be formed by depositing one metal layer on the piezoelectric layer **1010** and patterning the metal layer. In embodiments, the projection areas of the electrodes **1002**, **1006** and **1012** may have any suitable shape, such as square, rectangle, circle, and ellipse, so on.

As in the piezoelectric element **1000**, the first electrode (O) **1002** may be electrically connected to the conductor (O) **1004** using a metal, a via and interlayer dielectrics. In embodiments, the first electrode (O) **1002** may be in direct contact with the piezoelectric layer **1010**. The third conductor (T) **1014** may be deposited or grown on the other side of the piezoelectric layer **1010** with respect to the first electrode (O) **1002**.

FIG. **10D** shows a schematic diagram of a piezoelectric element **1030** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1030** may include two sub piezoelectric elements (or shortly sub elements) **1031-1** and **1031-2**. In embodiments, each sub element may be a three terminal device, i.e. it may have one top electrode **1032-1** (or **1032-2**), two bottom electrodes **1034-1** (or **1034-2**) and **1036-1** (or **1036-2**), and one piezoelectric layer **1035-1** (or **1035-2**). In embodiments, the top electrode **1032-1** may be electrically connected to the top electrode **1032-2** by a common conductor (O) **1031**, the first bottom electrode (X) **1034-1** may be electrically connected to the first bottom electrode (X) **1034-2** by a common

conductor (X) **1038**, and the second bottom electrode (T) **1036-1** may be electrically connected to the second bottom electrode (T) **1036-2** by a common conductor (T) **1040**. In embodiments, the piezoelectric element **1030** may be disposed on one membrane or each sub element may be disposed on a separate membrane. It should be apparent to those of ordinary skill in the art that the conductor (O) **1032-1** may be electrically connected to the electrode (O) **1031**, using metals, vias, interlayer dielectrics (ILD), so on, in the similar manner as the piezoelectric element illustrated in FIGS. **12-16**.

In embodiments, the conductor (X) **1038** and the conductor (T) **1040** may be all grounded (or connected to a DC bias) during active operation of the imager. In embodiments, the electrodes (O) **1032-1** and **1032-2** may be driven by a common transmit driver circuit and a common electrical signal, typically a signal waveform around the center frequency of the transducer. For example, if the center frequency is 2 MHz, a sinusoidal waveform or square waveform at 2 MHz is applied to the piezoelectric element **1030**. This waveform may cause the piezoelectric element **1030** to resonate at 2 MHz and send out a pressure wave, such as **122**, from the surface of the transducer. The pressure wave may be reflected from the target organ to be imaged. In embodiments, the reflected pressure wave may hit the piezoelectric element **1030** which is now connected to a signal receiver. The pressure wave may be converted to the electrical charge in the piezoelectric element **1030** by the piezoelectric layers **1035-1** and **1035-2**. In embodiments, this charge may be signal processed by amplifiers, filters and eventually digitized by an A/D converter (not shown in FIG. **10D**), followed by digital decimators with the data eventually interfaced to FPGAs or Graphical Processing Units (GPUs). These processed signals from multiple piezoelectric elements may be then reconstructed into images. The signal waveform driving the transmit driver can also be a frequency varying signal or a phase varying signal or other complex coded signals, such as chirps or Golay codes.

FIG. **10E** shows a schematic diagram of a piezoelectric element **1050** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1050** may include two sub elements **1051-1** and **1051-2**. In embodiments, each sub element may be a two terminal device, i.e. it may have one top electrode **1052-1** (or **1052-2**), one bottom electrode **1054-1** (or **1054-2**), and one piezoelectric layer **1056-1** (or **1056-2**). In embodiments, the top electrode (O) **1052-1** may be electrically connected to the top electrode (O) **1052-2** by a common conductor (O) **1051**, and the bottom electrode (X) **1054-1** may be electrically connected to the bottom electrode (X) **1054-2** by a common conductor (X) **1058**. In embodiments, the piezoelectric element **1050** may be disposed on one membrane or each sub element may be disposed on a separate membrane.

FIG. **10F** shows a schematic diagram of a piezoelectric element **1070** according to embodiments of the present disclosure. FIG. **10G** shows a bottom view of the piezoelectric element **1070** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1070** may include: a top electrode (O) **1074**, a first bottom electrode (X) **1080**; a second bottom electrode (T) **1076**; a piezoelectric layer **1075** disposed between the top and bottom electrodes; and three conductors **1072**, **1078** and **1082** that are electrically coupled to the bottom and top electrodes **1074**, **1076** and **1080**, respectively. (In FIG. **10G**, the conductors are not shown.) In embodiments, each of the first and second

bottom electrodes has an annular shape and the second bottom electrode (X) **1076** surrounds the first bottom electrode (T) **1080**.

FIG. **10H** shows a schematic diagram of a piezoelectric element **1085** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1085** may utilize transverse mode of operation and include: a substrate **1091**, a membrane **1090** secured to the substrate at one end; a bottom electrode (O) **1092** that is electrically coupled to a conductor **1089**; a piezoelectric layer **1088**; and a top electrode **1086** that is electrically coupled to a conductor **1087**. In embodiments, the membrane **1090** may be secured to the substrate **1091** at one end so as to vibrate in the transverse mode, as indicated by an arrow **1093**, i.e., the piezoelectric element may operate in the transverse mode.

It is noted that the piezoelectric element **1085** may have any suitable number of top electrodes. Also, it is noted that more than one piezoelectric element may be installed on the membrane **1090**. It is further noted that the substrate **1091** and membrane **1090** may be formed of one monolithic body and the membrane is formed by etching the substrate.

FIG. **11** shows a schematic diagram of a piezoelectric element **1100** according to embodiments of the present disclosure. As depicted, an electrode (O) **1104** may be disposed on the top surface of a piezoelectric layer **1110** and electrically connected to a conductor (O) **1102** that may be connected to an electric circuit. The conductor (T1) **1108**, conductor (T2) **1114** and conductor (X) **1118** may be connected to the bottom electrode (T1) **1106**, electrode (T2) **1112** and electrode (X) **1116**, respectively. The electrode (T1) **1106**, the electrode (X) **1116** and the electrode (T2) **1112** may be disposed on the bottom surface of the piezoelectric layer **1110**. In embodiments, the piezoelectric element **1100** may be disposed on one membrane or three separate membranes.

FIGS. **10A-11** show piezoelectric elements (or sub elements) that each have either two terminal (O and X) or three terminals (O, X, and T) or four terminals (O, X, T1 and T2). However, it should be apparent to those of ordinary skill in the art that more than a piezoelectric element (or sub element) may have more than four terminals. For instance, a piezoelectric element may have top bottom (O) electrode and more than three bottom electrodes.

FIG. **12-16** show steps for fabricating an exemplary piezoelectric element that has four terminals according to embodiments of the present disclosure. FIG. **12** show top view of a membrane **1206**, which may be formed by forming a membrane layer **1204** on a substrate **1202**, and forming a cavity **1208** in the substrate. FIG. **13** shows a cross sectional view of the structure in FIG. **12**, taken along the line **12-12**. In embodiments, the membrane **1204** may be deposited by a suitable wafer processing technique.

FIG. **14** shows a top view of a layer structure formed on the membrane layer **1204** and FIG. **15** shows a cross sectional view of the layer structure in FIG. **14**, taken along the line **14-14**, according to embodiments of the present disclosure. As depicted, three top electrodes **1223**, **1224-1**, and **1224-2**, a piezoelectric layer **1220**, and a bottom electrode **1222**, may be formed on the membrane layer **1204**. In embodiments, the top electrodes **1223**, **1224-1**, and **1224-2**, piezoelectric layer **1220**, and bottom electrode **1222** may be deposited by suitable wafer processing techniques, such as deposition, sputtering, patterning so on.

FIG. **16** shows a top view of a piezoelectric element **1600** according to embodiments of the present disclosure. As depicted, three conductors **1620**, **1622-1**, and **1622-2** may be electrically coupled to the electrodes **1223**, **1224-1**, and

1224-2, respectively. Also, the conductors (O) **1610** may be electrically coupled to the bottom electrode **1222** through one or more vias **1614**. In embodiments, electrical grounds and source planes may be reached to the bottom electrode **1222** through the vias **1614** and the conductors (O) **1610**. In embodiments, each of the conductors **1620**, **1622-1**, and **1622-2** may be connected to the ground or a DC bias voltage. In embodiments, the conductor **1620**, may be connected to the ground or a first DC bias voltage, and the conductors **1622-1** and **1622-2** may be connected to the ground or a second DC bias voltage.

In general, due to the inherent non-symmetry in the crystalline structure of piezoelectric material, an electrical polarity develops, creating electric dipoles. In a macroscopic crystalline structure, the dipoles are by default found to be randomly oriented as shown in FIG. **17A** on the left. When the material is subjected to a mechanical stress, each dipole rotates from its original orientation toward a direction that minimizes the overall electrical and mechanical energy stored in the dipole. If all the dipoles are initially randomly oriented (i.e. a net polarization of zero), their rotation may not significantly change the macroscopic net polarization of the material; hence, the piezoelectric effect exhibited will be negligible. Therefore, during an initial state, the dipoles need to be more-or-less oriented in the same direction, which is referred to as poling process. The direction along which the dipoles align is known as the poling direction. FIG. **17** shows dipole orientations of a piezoelectric material before, during and after the poling process according to embodiments of the present disclosure.

As depicted, before the poling process, the individual dipole moments are not aligned. During the poling process, the dipole moments may be aligned to point the same direction. After poling, the dipole moments may remain fairly aligned, although there may still be some elements of random direction. In embodiments, the poling process may be performed by putting the piezoelectric material in a constant electric field at a high temperature to thereby force the dipoles to align.

In embodiments, the piezoelectric element **1000** in FIG. **10A** may be poled so that the portions of the piezoelectric layer over the electrode (X) **1006** and electrode (T) **1012** may be poled in opposite directions, as shown, for example, in FIG. **10B** where the portion of the piezoelectric layer **1010** under the electrode (X) **1006** is poled in a first direction and the portion of the piezoelectric layer **1010** under the electrode (T) **1012** is poled in a second direction that is opposite the first direction. This type of poling may result in boosted pressure output for the same transmit voltage, compared to the pressure output that would be obtained using the one poling direction configuration. Also, in embodiments, this type of poling may improve the receive sensitivity, where the reflected pressure waves may be differentially boosted to create a larger charge output, compared to the one poling direction configuration.

FIG. **17B** shows a flow chart of an illustrative process for poling a piezoelectric element **1600** according to embodiments of the present disclosure. To pole the piezoelectric element **1600**, the piezoelectric element **1600** may be mounted inside a high temperature chamber (step **1728**) and the bottom electrode **1222** may be coupled to the ground (step **1722**), while the first top electrode **1224-1** (or **1224-2**) may be coupled to a high positive voltage, such as 15 V, (step **1724**) and the second top electrode **1223** may be coupled to a high negative voltage, such as -15 V, (step

1726). Then, the piezoelectric element **1600** may be subject to a high temperature inside the chamber for extended period of time (step **1728**).

Depending on the polarities of the first and second high voltages, the portions of the piezoelectric layer **1220** under the two electrodes **1224-1** and **1224-2** may be polarized in the same or opposite direction to that of the portion of the piezoelectric layer **1220** under the electrodes **1223**. In embodiments, for instance, poling may be implemented by application of high voltages across the electrodes at high temperature, typically 150° C., for 30 minutes for certain piezoelectric materials. For example, for a 1 μm thick piezoelectric layer, +15 V from the signal electrode to the T electrode and -15V from the signal electrode to the X electrode may be applied. Once the piezoelectric material is poled, then each of the X and T electrodes may be grounded or tied to a non-zero DC bias voltage while the conductor (O) **1610** may be connected to an ASIC chip so as to be driven by a transmit driver during the transmit operation or may be connected to an LNA (such as **1811** in FIG. **18A**) in the ASIC chip during the receive operation. In embodiments, a DC bias voltage may improve the sensitivity of the piezoelectric element **1600**.

FIG. **18A** shows an imaging assembly **1800** according to embodiments of the present disclosure. As depicted, the imaging assembly **1800** may include: a transceiver substrate **1802** (which may be similar to the transceiver tile **210**); and an ASIC chip **1804** electrically coupled to the transceiver substrate. In embodiments, the transceiver substrate **1802** may include one or more piezoelectric elements **1806**, where each of the piezoelectric element may be disposed on one or more membranes. In embodiments, more than one piezoelectric element may be disposed on one membrane. In embodiments, poling of the piezoelectric layer may be performed after the transceiver substrate **1802** is interconnected to the ASIC chip **1804**. It is noted that the ASIC **1804** may be replaced by a suitable substrate that includes multiple circuits for driving the piezoelectric elements **1806** in the transceiver substrate **1802**.

In embodiments, poling may be performed on the transceiver tile/substrate **1802** after the transceiver substrate is 3D interconnected to the ASIC chip **1804**. In the conventional piezoelectric elements, it is difficult to perform the poling process on a transceiver tile after the transducer tile is coupled to the circuits for driving the piezoelectric elements. It is due to the fact that poling requires application of high voltages to the circuits for controlling the piezoelectric elements and the high voltages may damage the circuits. In contrast, in embodiments, the poling may be performed on the transducer substrate **1802** that is already integrated with the ASIC chip **1804**. In embodiments, the ASIC chip **1804** may enable application of desired voltages on all first electrodes of the piezoelectric elements and high voltages may be applied to all second or additional electrodes.

In embodiments, each of the piezoelectric elements **1806a-1806n** may have two or more electrodes and these electrodes may be connected to drive/receive electronics housed in the ASIC chip **1804**. In embodiments, each piezoelectric element (e.g. **1806a**) may include a top conductor that is electrically connected to a conductor (O) (e.g. **1814a**) and two bottom electrodes that are electrically connected to conductors (X,T) (e.g. **1810a** and **1812a**). In embodiments, the conductor **1810a** may be electrically coupled to a DC bias (X) **1832a** or the ground, and the conductor (T) **1812a** may be coupled to a DC bias (T) **1834a** or the ground.

In embodiments, the ASIC chip **1804** may include one or more circuits **1842a-1842n** that are each electrically coupled to one or more piezoelectric elements **1806a-1806n**; and one control unit **1840** for controlling the circuits **1842a-1842n**. In embodiments, each circuit (e.g. **1842a**) may include a transmit driver (**1813a**), a receiver amplifier (or shortly amplifier) (e.g. **1811a**), a switch (e.g. **1816a**) having one terminal electrically coupled to the conductor (O) (**1814a**) and another terminal that toggles between the two conductors coupled to the transmit driver **1813a** and amplifier **1811a**. During a transmit (Tx) mode/process, the switch **1816a** may connect the transmit driver **1813a** to the piezoelectric element **1806a** so that a signal is transmitted to the top electrode of the piezoelectric element **1806a**. During a receive (Rx) mode/process, the switch **1816a** may connect the amplifier **1811a** to the piezoelectric element **1806a** so that a signal is transmitted from the top electrode of the piezoelectric element **1806a** to the amplifier **1811a**.

It is noted that the transmit driver **1813a** may include various electrical components. However, for brevity, the transmit driver **1813a** is represented by one driver. But, it should be apparent to those of ordinary skill in the art that the transmit driver may include a more complex driver with many functions. Electrical components for processing the received signals may be connected to the amplifier **1811a**, even though only one amplifier **1811a** is shown in FIG. **18A**. In embodiments, the amplifier **1811a** may be a low noise amplifier (LNA). In embodiments, the circuit **1842n** may have the same or similar structure as the circuit **1842a**.

In embodiments, all of the DC biases (X) **1832a-1832n** may be connected to the same DC bias or the ground, i.e., all of the conductors (X) **1810a-1810n** may be connected to a single DC bias or the ground. Similarly, all of the DC biases (X) **1834a-1834n** may be connected to the same DC bias or a different DC bias, i.e., all of the conductors (T) **1812a-1812n** may be connected to a single DC bias or the ground.

In embodiments, the conductors (X, T and O) **1810**, **1812**, and **1814** may be connected to the ASIC chip **1804** using an interconnect technology—for instance, copper pillar interconnects or bumps (such as **1882** in FIG. **18B**), as indicated by an arrow **1880**. In embodiments, the circuitry components in the ASIC chip **1804** may communicate outside the ASIC chip **1804** using an interconnect **1830**. In embodiments, the interconnect **1830** may be implemented using bonding wires from pads on the ASIC chip **1804** to another pad outside the ASIC chip. In embodiments, other types of interconnects, such as bump pads or redistribution bumps on the ASIC chip **1804** may be used in addition to wire bonded pads.

In embodiments, the LNAs **1811** included in the circuits **1842** may be implemented outside the ASIC chip **1804**, such as part of a receive analog front end (AFE). In embodiments, a LNA may reside in the ASIC chip **1804** and another LNA and programmable gain amplifier (PGA) may reside in the AFE. The gain of each LNA **1811** may be programmed in real time, allowing the LNA to be part of a time gain compensation function (TGC) needed for the imager.

In embodiments, the LNAs **1811** may be built using low voltage transistor technologies and, as such, may be damaged if they are exposed to high transmit voltages that the conventional transducers need. Therefore in the conventional systems, a high voltage transmit/receive switch is used to separate the high transmit voltages from the low voltage receive circuitry. Such a switch may be large and expensive, use High Voltage (HV) processes, and degrade the signal sent to LNA. In contrast, in embodiments, low

voltages may be used, and as such, the high voltage components of the conventional system may not be needed any more. Also, in embodiments, by eliminating the conventional HV switch, the performance degradation caused by the conventional HV switch may be avoided.

In embodiments, the piezoelectric elements **1806** may be connected to the LNAs **1811** during the receive mode by the switches **1816**. The LNAs **1811** may convert the electrical charge in the piezoelectric elements **1806** generated by the reflected pressure waves exerting pressure on the piezoelectric elements, to an amplified voltage signal with low noise. The signal to noise ratio of the received signal may be among the key factors that determine the quality of the image being reconstructed. It is thus desirable to reduce inherent noise in the LNA itself. In embodiments, the noise may be reduced by increasing the transconductance of the input stage of the LNAs **1811**, such as using more current in the input stage. The increase in current may cause the increase in power dissipation and heat. In embodiments, pMUTs **1806** may be operated with low voltages and be in close proximity to the ASIC chip **1804**, and as such, the power saved by the low voltage pMUTs **1806** may be utilized to lower noise in the LNAs **1811** for a given total temperature rise acceptable, compared to conventional transducers operated with high voltages.

FIG. **18B** shows a schematic diagram of an imaging assembly **1850** according to embodiments of the present disclosure. In embodiments, the transceiver substrate **1852** and ASIC chip **1854** may be similar to the transceiver substrate **1802** and ASIC chip **1804**, respectively. In the conventional systems, the electronics for driving piezoelectric transducers is typically located far away from the piezoelectric transducers and are connected to the piezoelectric transducers using a coax cable. In general, the coax cable increases parasitic loading, such as additional capacitance, on the electronics, and the additional capacitance causes loss in critical performance parameters, such as increase in noise and loss of signal power. In contrast, as depicted in FIG. **18B**, the transmit driver or drivers (or equivalently circuits) **1862a-1862n** may be connected directly to piezoelectric elements (or equivalently pixels) **1856a-1856n+i** using a low impedance three dimensional (3D) interconnect mechanism (as indicated by an arrow **1880**), such as Cu pillars or solder bumps **1882**, or wafer bonding or similar approaches or a combination of such techniques. In embodiments, upon integrating the transceiver substrate **1852** to the ASIC chip **1854**, the circuits **1862** may be located less than 100 μm vertically (or so) away from the piezoelectric elements **1856**. In embodiments, any conventional device for impedance matching between driver circuits **1862** and piezoelectric elements **1856** may not be required, further simplifying design and increasing power efficiency of the imaging assembly **1800**. Impedance of the circuits **1862** may be designed to match the requirement of the piezoelectric elements **1856**.

In embodiments, in FIG. **18A**, each of the piezoelectric elements **1806a-1806n** may be electrically connected to a corresponding one of the circuits **1842a-1842n** located in the ASIC chip **1804**. In embodiments, this arrangement may allow the imager to generate three-dimensional images. Similarly, in FIG. **18B**, each of the piezoelectric elements **1856a-1856m** may have three leads represented by X, T, and O. The leads from each of the piezoelectric elements may be electrically connected to a corresponding one of the circuits **1862a-1862m** located in the ASIC chip **1854** by the interconnect means **1882**. In addition, in embodiments, a line of piezoelectric elements, such as **1856n+1-1856n+i** may be

electrically coupled to one common circuit **1862n**. In embodiments, the transmit driver circuit **1862n** may be implemented with one transmit driver. In alternative embodiment, the transmit driver circuit **1862n** may be implemented with multilevel drivers to facilitate various imaging modes.

It should be apparent to those of ordinary skill in the art that the ASIC chip **1854** may have any suitable number of circuits that are similar to the circuit **1862n**. In embodiments, the control unit **1892** may have capability to configure the piezoelectric elements, either horizontally or vertically in a two dimensional pixel array, configure their length and put them into transmit or receive or poling mode or idle mode. In embodiments, the control unit **1892** may perform the poling process after the transceiver substrate **1852** is combined with the ASIC chip **1854** by the three dimensional integration technique **1882**. In embodiments, the transmit driver circuit **1843** may be implemented with multilevel drive as shown in FIG. **34**, where the transmit driver output may have more than 2 output levels. FIG. **34** shows an embodiment where the output level may be 0V or 6V or 12V. It is understood that that these voltages can be different, for example they can be -5V, 0V and +5V. The transmit driver can also be a 2 level driver with drive signal as shown in FIG. **33**.

In embodiments, lead lines **1882a-1882n** may be signal conductors that are used to apply pulses to the electrodes (O) of the piezoelectric elements **1856**. Similarly, the lead lines **1884a-1884n**, **1886a-1886n**, and **1888a-1888n** may be used to communicate signals with the piezoelectric elements **1856a-1856n+i**. It is noted that other suitable number of lead lines may be used to communicate signals/data with the imaging assembly **1800**.

In embodiments, each of the lead lines (X) **1886** and lead lines (T) **1888** may be connected to the ground or a DC bias terminal. In embodiments, the digital control lead **1894** may be a digital control bus and include one or more leads that are needed to control and address the various functions in the imaging assembly **1850**. These leads, for example, may allow programmability of the ASIC chip **1854** using communication protocols, such as Serial Peripheral Interface (SPI) or other protocols.

In embodiments, the piezoelectric elements **1806** (or **1856**) and the control electronics/circuits **1842** (or **1862**) may be developed on the same semiconductor wafer. In alternative embodiments, the transceiver substrate **1802** (or **1852**) and ASIC chip **1804** (or **1854**) may be manufactured separately and combined to each other by a 3D interconnect technology, such as metal interconnect technology using bumps **1882**. In embodiments, the interconnect technology may eliminate the low yield multiplication effect, to thereby lower the manufacturing cost and independently maximize the yield of components.

In embodiments, lead lines **1862a-1862n** may be signal conductors that are used to apply pulses to the electrodes (O) of the piezoelectric elements **1806**. Similarly, the lead lines **1864a-1864n**, **1866a-1866n**, and **1868a-1868n** may be used to communicate signals with the piezoelectric elements **1806a-1806n**. It is noted that other suitable number of lead lines may be used to communicate signals/data with the imaging assembly **1800**.

As discussed above, the LNAs **1811** may operate in a charge sensing mode and each have a programmable gain that may be configured in real time to provide gain compensation. In embodiments, as discussed in conjunction with FIG. **3B**, one or more temperature sensors may be installed in the imager **120**. In embodiments, the ASIC may receive

temperature data from the temperature sensor(s) and, using the temperature data, adjust the imaging frame rate or a signal-to-noise ratio of the LNAs **1811**.

FIG. **19A-1** shows a top view of a transceiver substrate **1902** and an ASIC chip **1906** and FIG. **19A-2** shows a side view of imaging assembly **1901** according to embodiments of the present disclosure. As depicted, the imaging assembly **1901** may include the transceiver substrate **1902** that is interconnected to the ASIC chip **1906** by suitable interconnection mechanism, such as bumps. Hereinafter, the bumps are shown as the interconnection mechanism, even though other suitable interconnection mechanisms may be used in place of the bumps.

In embodiments, each piezoelectric element **1904** may be a two terminal piezoelectric element, where the piezoelectric element is symbolically represented by two electrodes O and X. In embodiments, the circuit element **1908** may include electrical components for driving the corresponding piezoelectric element **1904**, where the circuit element **1908** is symbolically represented by a transmit driver. In embodiments, an imaging element **1910** may include a piezoelectric element **1904** and a circuit element **1908**, and the piezoelectric element **1904** may be electrically connected to the circuit element **1908** by two bumps.

FIG. **19B-1** shows a top view of a transceiver substrate **1911** and an ASIC chip **1913** and FIG. **19B-2** shows a side view of imaging assembly **1915** according to embodiments of the present disclosure. As depicted, the imaging assembly **1915** may be similar to the imaging assembly **1901**, with the difference that two sub piezoelectric elements are electrically coupled to two sub circuit elements by three bumps. More specifically, the piezoelectric element **1912** includes two sub piezoelectric elements, each sub piezoelectric element may be a two terminal piezoelectric element, and the X electrodes of the two sub piezoelectric elements may be electrically coupled to each other. In embodiments, each O electrode of the sub piezoelectric element may be electrically coupled to a transmit driver of the corresponding sub circuit element **1914** and the X electrodes of the two sub piezoelectric elements may be electrically coupled to a common electrical terminal of the circuit element **1914**. As such, in each imaging element **1917**, the piezoelectric element **1912** may be interconnected to the circuit element **1914** by three bumps.

FIG. **19C** shows a top view of a transceiver substrate **1920** and an ASIC chip **1924** according to embodiments of the present disclosure. As depicted, the transceiver substrate **1920** may be similar to the transceiver substrate **1902**, with the difference that three sub piezoelectric elements are electrically coupled to three sub circuit elements by four bumps. More specifically, the piezoelectric element **1922** includes three sub piezoelectric elements, each sub piezoelectric element may be a two terminal piezoelectric element, and the X electrodes of the three sub piezoelectric elements may be electrically coupled to each other. In embodiments, each O electrode of the sub piezoelectric element may be electrically coupled to a transmit driver of the corresponding sub circuit element and the X electrodes of the three sub piezoelectric elements may be electrically coupled to a common electrical terminal of the circuit element **1926**. As such, the piezoelectric element **1922** may be interconnected to the circuit element **1926** by four bumps.

It is noted that the piezoelectric element may have more than two terminals. FIG. **19D** shows a top view of a transceiver substrate **1930** and an ASIC chip **1934** according to embodiments of the present disclosure. As depicted, the transceiver substrate **1930** may be similar to the transceiver

substrate **1902**, with the difference that each piezoelectric element **1932** may be electrically coupled to a circuit element **1936** by three bumps. In embodiments, the O electrode may be coupled to a transmit driver of the circuit element **1936** by a bump, and the X and T electrodes may be coupled to the circuit element **1936** by two bumps.

FIG. **19E** shows a top view of a transceiver substrate **1940** and an ASIC chip **1944** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1942** may include two sub piezoelectric elements, each sub piezoelectric element may be a three terminal piezoelectric element, and the X electrodes of the two sub piezoelectric elements may be electrically coupled to each other. In embodiments, each O electrode of the sub piezoelectric element may be electrically coupled to a transmit driver of the corresponding sub circuit element by a bump and the X electrodes of the two sub piezoelectric elements may be electrically coupled to the circuit element **1946** by a bump and each T electrode of the sub piezoelectric element may be electrically coupled to the circuit element **1946** by a bump. As such, the piezoelectric element **1942** may be interconnected to the circuit element **1946** by five bumps.

FIG. **19F** shows a top view of a transceiver substrate **1950** and an ASIC chip **1954** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1952** may include two sub piezoelectric elements, each sub piezoelectric element may be a three terminal piezoelectric element, the X electrodes of the two sub piezoelectric elements may be electrically coupled to each other, and T electrodes of the two sub piezoelectric elements may be electrically coupled to each other. In embodiments, each O electrode of the sub piezoelectric element may be electrically coupled to a transmit driver of the corresponding sub circuit element by a bump and the X electrodes of the two sub piezoelectric elements may be electrically coupled to the circuit element **1956** by a bump. Also, the T electrodes of the two sub piezoelectric elements may be electrically coupled to the circuit element **1956** by a bump. As such, the piezoelectric element **1952** may be interconnected to the circuit element **1956** by four bumps.

FIG. **19G** shows a top view of a transceiver substrate **1960** and an ASIC chip **1964** according to embodiments of the present disclosure. As depicted, the piezoelectric element **1962** may include two sub piezoelectric elements, each sub piezoelectric element may be a three terminal piezoelectric element, the O electrodes of the two sub piezoelectric elements may be electrically coupled to each other, the X electrodes of the two sub piezoelectric elements may be electrically coupled to each other, and the T electrodes of the two sub piezoelectric elements may be electrically coupled to each other. As such, the piezoelectric element **1962** may be interconnected to the circuit element **1966** by three bumps.

FIG. **20** shows a schematic diagram of an $m \times n$ array **2000** of piezoelectric elements **2002-11-2002- mn** according to embodiments of the present disclosure. As depicted, each piezoelectric element may be a two terminal piezoelectric element (such as piezoelectric element **900** in FIG. **9**) and have an electrode (O) (e.g. **2003-11**) electrically coupled to a conductor (O) (e.g. **2004-11**) and an electrode (X) electrically connected to ground or a DC bias voltage via a common conductor (X) **2007**. In embodiments, each signal conductor (O) may be managed independently by a circuit element (such as **1908**). In embodiments, each conductor (O) (e.g. **2004- mn**) may be electrically coupled to a transmit driver of a circuit element while all of the X electrodes (**2006-11-2006- mn**) of the piezoelectric element array may

be connected to a common conductor (X) **2007**. In embodiments, the array **2000** may be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $m \times n + 1$ bumps, as discussed in conjunction with FIGS. **19A-19G**. More specifically, the $m \times n$ conductors (O) **2004-11-2004- mn** may be coupled to $m \times n$ transmit drivers of ASIC chip by $m \times n$ bumps and the common conductor (X) **2007** may be coupled to the ASIC chip by one bump. In embodiments, such an exemplary arrangement as described here is used to perform 3D imaging, where each piezoelectric element, including at least one sub piezoelectric element, can provide unique information in the array. In embodiments, each piezoelectric element may have one or more membranes and vibrate in multiple modes and frequencies of the membranes. In embodiments, each piezoelectric element **2002** may be driven by pulses that have voltage profiles **3300** and **3400** in FIGS. **33** and **34**.

In embodiments, the o electrodes in each column (e.g. **2003-11-2003- $m1$**) may be electrically coupled to a common conductor. For instance, the circuit elements in the ASIC chip may be electronically controlled so that the O electrodes in each column may be electrically coupled to each other. In such a configuration, the O electrodes in each column may receive the same electrical pulse through a common transmit driver or per a multiplicity of drivers with identical electrical drive signals during the transmit mode. Similarly, the O electrodes in each column may simultaneously transmit the electrical charge to a common amplifier during the receive mode. Stated differently, the piezoelectric element in each column may be operated as a line unit (or equivalently line element).

FIG. **21** illustrates a schematic diagram of an $n \times n$ array **2100** of piezoelectric elements **2102-11-2102- mn** according to embodiments of the present disclosure. As depicted, each piezoelectric element may be a three terminal piezoelectric element and include the electrodes O, X, and T. In embodiments, the X electrodes (e.g. **X11**, **X21**, . . . , **X $m1$**) may be connected column wise in a serial manner and all of the X electrodes (**X11-X mn**) may be electrically coupled to a common conductor (X) **2106**. The T electrodes (e.g. **T11**, **T21**, . . . , **T $m1$**) may be connected column wise in a serial manner and all of the T electrodes (**T11-T mn**) may be electrically coupled to a common conductor (T) **2108**. A column of elements such as **2102-11**, **2102-21** through **2102- $m1$** when connected together as described in embodiments make up a line element or a column. In embodiments, each of the O electrodes **2103-11-2103- mn** may be electrically coupled to a transmit driver of a corresponding circuit element in an ASIC chip via one of the conductors **O11-O mn** . In embodiments, the array **2100** may be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $m \times n + 2$ bumps.

In embodiments, the O electrodes in each column (e.g. **2103-11-2103- $m1$**) may be electrically coupled to a common conductor. In such a configuration, the O electrodes in each column may receive the same electrical pulse through a common transmit driver during the transmit mode. Similarly, the O electrodes in each column may simultaneously transmit the electrical charge to a common amplifier during the receive mode. Stated differently, the piezoelectric element in each column is operated as a line unit. In embodiments each of the O electrodes in a column may be connected to a dedicated transmit driver, where the input signal of the transmit drivers for all elements in a column are identical, thus creating a substantially identical transmit drive output to appear on all piezoelectric elements during a

transmit operation. Such a line element is electronically controlled on a per element basis, since each element has its own transmit driver. This has advantages in driving large capacitive line elements, where each element has smaller capacitance and delays in timing can be minimized for elements on a column. In embodiments, in a receive mode, charge from all elements in a column can be sensed by connecting it to a LNA, as is done by 2D imaging. For 3D imaging, charge for each element is sensed by connecting the O electrodes of each element to a LNA during a receive mode operation.

FIG. 22 illustrates a schematic diagram of an $m \times n$ array 2200 of piezoelectric elements 2202-11-2202- mn according to embodiments of the present disclosure. As depicted, the array 2200 may be similar to the array 2100, with the differences that the X electrodes (e.g. X12-X m 2) in a column may be connected to a common conductor (e.g. 2206-1) and the T electrodes (e.g. T12-T m 2) in a column may be connected to a common conductor (e.g. 2208-1). As such, the X electrodes (or T electrodes) in the same column may have the same voltage potential during operation. In embodiments, each of the O electrodes may be electrically coupled to a transmit driver of a corresponding circuit element in an ASIC chip via one of the conductors O11-O mn . In embodiments, the array 2200 may be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $m \times n + 2n$ bumps.

Compared to array 2100, the array 2200 may use more bumps for connecting the T and X electrodes to the ASIC chip. In general, an increase in the number of connections for T and X between the ASIC chip and the piezoelectric array may reduce impedance in the X and T conductors when connected in parallel to the ground or DC bias sources and reduce the crosstalk. Crosstalk refers to the coupling of signals from an imaging element to another one, and may create interference and reduce the image quality. Spurious electrical coupling may be created when any voltage drop due to current flowing in X and T lines appear across a piezoelectric element that ideally should not be exposed to that voltage. In embodiments, when the piezoelectric element is not transmitting or receiving under electronic control, the X, T, and O electrodes may be locally shorted. Alternatively, the idle electrodes have the O electrodes grounded, leaving the X electrodes connected to other X electrodes in the array and the T electrodes connected to other T electrodes in the array.

FIG. 23 illustrates a schematic diagram of an $m \times n$ array 2300 of piezoelectric elements 2302-11-2302- mn according to embodiments of the present disclosure. As depicted, the array 2300 may be similar to the array 2100, with the difference that each piezoelectric element may be a five terminal piezoelectric element, i.e., each piezoelectric element may include one bottom electrode (O) and four top electrodes (two X electrodes and two T electrodes). In embodiments, two X electrodes of each piezoelectric element may be connected column wise in a serial manner and all of the 2 $m \times n$ X electrodes may be electrically coupled to a common conductor (X) 2306. Similarly, the two T electrodes of each piezoelectric element may be connected column wise in a serial manner and all of the 2 $m \times n$ T electrodes may be electrically coupled to a common conductor (T) 2308. In embodiments, each of the O electrodes may be electrically coupled to a transmit driver of a corresponding circuit element in an ASIC chip via one of the conductors O11-O mn . In embodiments, the array 2300 may

be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $m \times n + 2$ bumps.

FIG. 24 illustrates a schematic of an $m \times n$ array 2400 of piezoelectric elements 2402-11-2402- mn according to embodiments of the present disclosure. As depicted, the array 2400 may be similar to the array 2200, with the differences that each piezoelectric element may be a five terminal piezoelectric element: one bottom electrode (O) and four top electrodes (two X electrodes and two T electrodes). In embodiments, the two X electrodes of each piezoelectric element may be electrically connected in a column wise direction to a conductor (e.g. 2406-1), and the two T electrodes of each piezoelectric element may be electrically connected in a column wise direction to a common conductor (e.g. 2408-1). In embodiments, each of the O electrodes may be electrically coupled to a transmit driver of a corresponding circuit element in an ASIC chip via one of the conductors O11-O mn . In embodiments, the array 2400 may be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $m \times n + 2n$ bumps.

FIG. 25 illustrates a schematic diagram of an $m \times n$ array 2500 of piezoelectric elements 2502-11-2502- mn according to embodiments of the present disclosure. As depicted, the array 2500 may be similar to the array 2100 in that each piezoelectric element may have one bottom electrode (O) and two top electrodes (T), but have the differences that all of the two top electrodes (T) of the piezoelectric elements along a column (e.g. 2502-11-2502- m 1) may be electrically connected to a common conductor (e.g. 2508-1). In embodiments, each of the O electrodes may be electrically coupled to a transmit driver of a corresponding circuit element in an ASIC chip via one of the conductors O11-O mn . In embodiments, the array 2500 may be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $m \times n + n$ bumps.

FIG. 26 illustrates a schematic of an $m \times n$ array 2600 of piezoelectric elements 2602-11-2602- mn according to embodiments of the present disclosure. As depicted, the array 2600 may have similar electrical connections to the array 2100, i.e., all of the X electrodes in the piezoelectric elements may be electrically coupled to a common conductor 2606 and all of the T electrodes in the piezoelectric elements may be electrically coupled to a common conductor 2608. The array 2600 may be different from the array 2100 in that the top electrodes (X, T) of one piezoelectric element (e.g. 2602-11) may have the same or different geometrical shapes from the top electrodes (X, T) of another piezoelectric element (e.g. 2602-21).

For the piezoelectric arrays 2000-2500, the piezoelectric elements in each piezoelectric array may be the same or different from each other. For instance, the projection areas of the two top electrodes of one piezoelectric element 2202-11 may have same or different shapes from the projection areas of the two top electrodes of another piezoelectric element 2202- n 1.

FIG. 27 illustrates a schematic diagram of an $m \times n$ array 2700 of piezoelectric elements 2702-11-2702- mn according to embodiments of the present disclosure. As depicted, each piezoelectric element may include two signal electrodes (O) and one common electrode (X). In embodiments, each signal electrode (O) may be electrically coupled to a transmit driver of a corresponding circuit element of an ASIC chip. For instance, the piezoelectric element 2702-11 may include two signal conductors O111 and O112 that may be electrically coupled to two circuit elements in an ASIC chip,

respectively, where each signal electrode may develop electrical charge during the receive mode. In embodiments, the array **2700** may be disposed on a transceiver substrate and electrically coupled to an ASIC chip by interconnection mechanism, such as $2 \times n + 1$ bumps. In embodiments, all of the T electrodes in the array **2700** may be electrically coupled to the ground or a DC bias voltage via the common conductor (T) **2708**.

In embodiments, the signal conductors (O) in the arrays in FIGS. **20-27** may be electrically coupled to a circuit element, where the circuit element may include a transistor switch that is similar to the switch **1816** in FIG. **18A**, i.e., the switch may toggle between the transmit driver and an amplifier during the transmit and receive modes, respectively so that the O electrode may generate pressure wave during the transmit mode and develop electrical charge during the receive mode.

FIG. **28** shows an exemplary embodiment of an imaging system **2800** according to embodiments of the present disclosure. As depicted, the imaging system **2800** may include an array of piezoelectric elements **2802-11-2802-mn** and circuit elements for controlling/communicating with the array. In embodiments, each of the piezoelectric elements **2802-11-2802-mn** may include three electrodes; first and second signal (O) electrodes and a T electrode. (For the purpose of illustration, the first and second O electrodes in each piezoelectric element refer to the left and right O electrodes of each piezoelectric element in FIG. **28**.) In embodiments, all of T electrodes in the array **2800** may be electrically coupled to the ground or DC bias voltage via the conductor (T) **2808**. In embodiments, the first O electrodes of the piezoelectric elements in a column may be electrically coupled to a common conductor (e.g. **O11**) and the second O electrodes of the piezoelectric elements in the same column may be electrically coupled to another common conductor (e.g. **O12**). In embodiments, during the receive mode, each of the first and second signal O electrodes may develop electrical charge that may be processed by a corresponding circuit.

In embodiments, the first set of conductors **O11, O21, . . . , On1** may be electrically coupled to the amplifiers **2810-1-2810-n**, respectively, where the electrical charge developed in a column of the first O electrodes may be transferred to a corresponding amplifier via one of the O conductors. In embodiments, the second set of conductors **O12, O22, . . . , On2** may be electrically coupled to the switches **2812-1-2812-n**, respectively. In embodiments, each switch (e.g. **2812-1**) may be connected to a transmit driver (e.g. **2816-1**) during the transmit mode/process so that a signal pulse may be transmitted to a column of second O electrodes in the piezoelectric elements (e.g. **2801-11-2802-m1**). In embodiments, each switch (e.g. **2812-1**) may be connected to a signal amplifier (e.g. **2814-1**) during the receive mode/process so that electrical charge developed in a column of second O electrodes in the piezoelectric elements (e.g. **2801-11-2802-m1**) may be transmitted to the amplifier. In embodiments, the piezoelectric elements **2802-11-2802-mn** may be disposed in a transceiver substrate while the switches **2812-1-2812-n**, transmit drivers **2816-1-2816-n**, and amplifiers **2810-1-2810-n** and **2814-1-2814-n** may be disposed in an ASIC chip, where the transceiver substrate may be electrically coupled to the ASIC chip by $2n+1$ bumps.

In embodiments, a column of the first electrodes may be electrically coupled to a common conductor (e.g. **O11**) and a column of the second electrodes may be electrically coupled to another common conductor (e.g. **O12**). As such,

in embodiments, the imaging system **2800** may be operated as a line imager, i.e., each of the first set of conductors **O11-On2** may operate as a transmit unit and/or a receive unit during operation. As discussed above, during the receive mode, the electrical charge developed in a column of the first O electrodes connected to a conductor (e.g. **O11**) may be transmitted to an amplifier (e.g. **2810-1**), which may be a low noise amplifier. Then, the amplifier may amplify the electrical charge signal and convert the charge signal to an output voltage. Thus, each column of the first O electrodes may operate as a receiving line imager. In embodiments, during the receive mode, the electrical charge developed in a column of the second O electrodes connected to a conductor (e.g. **O12**) may be transmitted to a signal amplifier (e.g. **2814-1**), which may be a low noise amplifier, via a switch (e.g. **2812-1**). Then, the amplifier may amplify the electrical charge signal and convert the charge signal to an output voltage. Thus, each column of the second O electrodes may operate as a receiving line imager. In embodiments, during the transmit mode, the electrical signal pulse may be transmitted from the transmit driver (e.g. **2816-1**) to a column of the second O electrodes connected to a conductor (e.g. **O12**) via a switch (e.g. **2812-1**) so that the set of second O electrodes may generate pressure waves. Thus, each column of second O electrodes may operate as a transmit line unit.

In embodiments, the switches **2812**, which may be transistor switches, may be set to a neutral position (i.e., they are not coupled to either transmit drivers or amplifiers) during the receive mode. In such a case, only the second set of conductors **O12, O22, . . . , On2** may operate during the receive mode.

In embodiments, the transmit driver (e.g. **2816-1**) may send a signal to a column of piezoelectric elements (e.g. **2802-11-2802-m1**) via a conductor (**O12**) and simultaneously, an amplifier (e.g. **2810-1**) may receive electrical charge signal from the same column of piezoelectric elements (e.g. **2802-11-2802-m1**). In such a case, each piezoelectric element (e.g. **2802-11**) in a column may receive a signal from the transmit driver (e.g. **2816-1**) through one conductor (e.g. **O12**) and simultaneously transmit an electrical charge signal to an amplifier (e.g. **2810-1**) via another conductor (e.g. **O11**), i.e., the imaging system **2800** may perform simultaneous transmitting and receiving modes. This simultaneous operation of transmitting and receiving modes may be very advantageous in continuous mode Doppler Imaging, where a high blood flow velocity may be imaged, compared to pulsed Doppler Imaging.

In embodiments, a line unit, which refers to a column of O electrodes electrically coupled to a common conductor, may operate as a transmit unit or a receive unit or both. For instance, electrical signals may be sequentially transmitted to the conductors **O12, O22, . . . , On2** so that the line elements sequentially generate pressure waves during the transmit mode, and the reflected pressure waves may be processed and combined to generate a two dimensional image of the target organ in the receive mode. In another example, electrical drive signals may be simultaneously transmitted to the conductors **O12, O22, . . . , On2** during the transmit mode and the reflected pressure waves may be processed at the same time using charge generated from conductors **O11, O12** to simultaneously transmit and receive ultrasound to create a two dimensional image. Conductors **O12-On2** may also be used to receive charge from the piezoelectric line elements in a receive mode of operation.

FIG. 29 shows an exemplary embodiment of an imaging system 2900 according to embodiments of the present disclosure. As depicted, the imaging system 2900 includes an array of piezoelectric elements 2902-11-2902-*mn* and each piezoelectric element may include first and second signal (O) electrodes and a T electrode. In embodiments, all of the T electrodes in the array may be electrically coupled to one common conductor (T) 2908; each row of the first O electrodes may be electrically connected to one of conductors O1-O_m; and each column of the second O conductors may be electrically connected to a switch 2912 via one of conductors O12-On2 and. In embodiments, each of the switches 2912-1-2912-*n* may toggle between a transmit driver (e.g. 2916-1) and an amplifier (e.g. 2914-1), which may be a low noise amplifier. In embodiments, each of the conductors O1-On may be connected to one of the amplifiers 2910-1-2910-*m*, which may be low noise amplifiers.

In embodiments, during the transmit mode, a signal may be transmitted from a transmit driver (e.g. 2916-1) to a column of second O electrodes via a conductor (e.g. O12) so that the column of piezoelectric elements may generate pressure waves as a line unit. During the transmit mode, each switch (e.g. 2912-1) may be toggled to a corresponding transmit driver (e.g. 2916-1).

In embodiments, the imaging system 2900 may process the reflected pressure waves in two different methods. In the first method, the amplifiers 2910-1-2910-*n* may receive electric charge signals from the first O electrodes, i.e., each amplifier may receive signals from a row of the first O electrodes. This method allows biplane imaging/mode, where for a two dimensional image, the biplane image may provide orthogonal perspectives. Also, this method may provide more than two dimensional imaging capability. The biplane imaging may be helpful for many applications, such as biopsy. It is noted that, in this method, the transmitting and receiving modes may be performed simultaneously. In the second method, the switches 2912 may be toggled to the amplifiers 2914 so that each amplifier may receive and process the electrical charge signals from a corresponding column of the second O electrodes.

In embodiments, a line unit, which refers to a column (or row) of O electrode electrically coupled to an O conductor, may operate as a transmit unit or a receive unit or both. In embodiments, even though the conductors O1-O_m are arranged in orthogonal directions to the conductors O12-On2, the directions may be electronically programmed and electronically adjustable. For instance, the gain of the amplifiers 2910 and 2914 may be adjustable electronically, where gain control leads are implemented in the amplifiers. In embodiments, the length of each line elements (i.e., the number of piezoelectric elements in each line element) may also be electronically adjusted. In embodiments, this may be achieved by connecting all signal electrodes of every piezoelectric element to corresponding nodes in the ASIC chip and, where the ASIC programs the connection between the signal electrodes of the elements to be connected to each other, transmit drivers or amplifiers as appropriate.

FIG. 30 shows an embodiment of a piezoelectric element 3000 coupled to a circuit element 3001 according to embodiments of the present disclosure. As depicted, the piezoelectric element 3000 may include: a first sub-piezoelectric element 3021-1 and a second sub-piezoelectric element 3021-2. The piezoelectric element 3000 may include: a bottom electrode (X) 3002 that is shared by the first and second sub piezoelectric elements and coupled to a conductor (X) 3006. In embodiments, the first sub-piezoelectric element 3021-1 may include a signal (O) electrode 3003 that

is electrically coupled to the amplifier 3010 via the conductor 3008. In embodiments, the second sub-piezoelectric element 3021-2 may include a signal (O) electrode 3004 that is electrically coupled to the switch 3014 via the conductor 3012.

In embodiments, a circuit element 3001 may be electrically coupled to the piezoelectric element 3000 and include two amplifiers 3010 and 3016, such as low noise amplifiers, and a transmit driver 3018. In embodiments, the switch 3014 may have one end connected to the O electrode 3004 through the conductor 3012 and the other end that may toggle between the amplifier 3016 for the receive mode and a transmit driver 3018 for the transmit mode. In embodiments, the amplifier 3016 may be connected to other electronics to further amplify, filter and digitize a receive signal, even though an amplifier is used to symbolically represent the electronics. The transmit driver 3018 may be a multi-stage drive and may generate an output with two or more levels of a signaling. The signaling can be unipolar or bipolar. In embodiments, the transmit driver 3018 may include a switch interconnecting an input to an output of a driver under electronic control of the driver, which is not explicitly shown in FIG. 30.

In embodiments, the signal of the transmit driver 3018 may be pulse width modulated (PWM), where, by controlling the pulse widths on a per element basis, a weighting function may be created on a transmitted ultrasound signal. This may for example perform a windowing function, where the transmit signal is weighted by a window function. In embodiments, the weighting coefficients may be achieved by varying the duty cycle of the transmit signal as is done during PWM signaling. This kind of operations may allow for transmit apodization, where the side lobe of a radiated signal are greatly attenuated, allowing for a higher quality image.

In embodiments, a transceiver array may be disposed in a transceiver substrate and include an *n*×*n* array of the piezoelectric element 3000 and an *n*×*n* array of the circuit elements 3001 may be disposed in an ASIC chip, where each piezoelectric element 3000 may be electrically coupled to a corresponding one of the *n*×*n* array of the circuit elements 3001. In such a case, the transceiver substrate may be interconnected to the ASIC chip by 3*n*² bumps. In embodiments, each column (or row) of piezoelectric element array may be operated a line unit, as discussed in conjunction with FIGS. 28 and 29. For instance, a same pulse may be simultaneously applied to a column of piezoelectric elements so that the column of piezoelectric elements may generate pressure waves simultaneously. It is noted that each piezoelectric element 3000 of the *n*×*n* array of piezoelectric elements may be coupled with a corresponding one circuit element 3001 of the *n*×*n* array of circuit elements.

In embodiments, the sub-piezoelectric element 3021-1 may be in the receive mode during the entire operational period while the sub-piezoelectric element 3021-2 may be in either transmit or receive mode. In embodiments, the simultaneous operation of transmit and receive modes may allow the continuous mode Doppler imaging.

In embodiments, when the transmit driver 3018 transmits a signal to the electrode 3004, the power levels of the pressure wave generated by the sub-piezoelectric element 3021-2 may be changed by using pulse width modulation (PWM) signaling. This is important, for example, when switching from B mode to Doppler Mode imaging, signal power transmitted into the human body may be long and if power levels are not reduced, tissue damage may occur. Typically, in the conventional systems, different fast settling

power supplies are used for B Mode and various Doppler Mode imaging to allow transmit drive voltages to differ in the 2 cases to for example not create excessive power in Doppler mode. Unlike the conventional systems, in embodiments, the power level may be changed by using the PWM signals on the transmit without using the conventional fast settling power supplies. In embodiments, rapid switching between Doppler and B mode imaging is desired to co-image these modes together. In embodiments, the ground electrodes of the piezoelectric element may also be separated from each other and connected to the ground separately. In embodiments, this independent grounding may reduce the noise and result in faster settling times. In embodiments, power transmitted may also be reduced by reducing the height of the transmit columns under electronic control. This again facilitates use of same power supply for both Doppler and B mode and meet power transmission requirements in each mode. This also allows co imaging.

FIG. 31 shows a circuit 3100 for controlling multiple piezoelectric elements according to embodiments of the present disclosure. In embodiments, the circuit 3100 may be disposed in an ASIC chip, where the line (either column or row) of piezoelectric elements that is disposed in a transceiver substrate and the ASIC chip may be interconnected to the transceiver substrate by bumps. As depicted, the circuit 3100 may include an array of circuit elements 3140-1-3140-*n*, where each circuit element may communicate signals with the O and X electrodes of the corresponding piezoelectric element.

As depicted in FIG. 31, each circuit element (e.g. 3140-1) may include a first switch (e.g. 3102-1), a second switch (e.g. 3104-1), a third switch (e.g. 3106-1), and a transmit driver (e.g. 3108-1). The output from the transmit driver (e.g. 3108-1) may be sent to an O electrode of the piezoelectric element via a conductor (e.g. 3110-1). During the transmit mode, each circuit element may receive a transmit driver (driving) signal 3124 through a conductor 3122. Each second switch (e.g. 3104-1), which may be transistor switches and controlled by a control unit 3150, may be turned on to transmit the signal 3124 to the transmit driver (e.g. 3108-1). (The electrical connections between the control unit 3150 and other components in the circuit 3100 are not shown in FIG. 31.) The transmit driver (e.g. 3108-1) may perform logical decode, level shift, buffer the input signal and send the transmit signal to the O electrode via the conductor (e.g. 3110-1). In embodiments, during the transmit mode, the first switch (e.g. 3102-1) may be turned off.

In embodiments, the control unit 3150 may decide which piezoelectric elements need to be turned on during the transmit mode. If the control unit 3150 decides not to turn on a second piezoelectric element, the first switch (e.g. 3102-2) and the second switch (e.g. 3104-2) may be turned off, while the third switch (e.g. 3106-2) may be turned on so that the O and X electrodes have the same electrical potential (i.e., there is a net zero volt drive across the piezoelectric layer). In in embodiments, the third switches 3106 may be optional.

In embodiments, during the receive mode, the first switch (e.g. 3102-1) may be turned on so that the electrical charge developed in the O electrode may be transmitted through the conductors 3110-1 and 3120 to the amplifier 3128. Then, the amplifier 3128 may receive electrical charge signal (or, equivalently, sensor signal) 3126 and amplify the sensor signal, where the amplified signal may be further processed to generate an image. During the receive mode, the second switch (e.g. 3104-1) and the third switch (e.g. 3106-1) may be turned off so that the received signal may not be inter-

ferred. It is noted that the entire array of the circuit element 3140-1-3140-*n* may share a common amplifier 3128, simplifying the design of the circuit 3100. In embodiments, the X electrodes of the piezoelectric elements may be electrically coupled to the ground or a DC bias voltage via the conductors 3112-1-3112-*n*, where the conductors 3112-1-3112-*n* may be electrically coupled to a common conductor 3152.

In embodiments, the circuit 3100 may be coupled to a column of piezoelectric elements (e.g. 2002-11-2002-*n*1) in FIG. 20. In embodiments, a plurality of circuits that are similar to the circuit 3100 may be coupled with the multiple columns of piezoelectric elements in the array in FIG. 20, and the conductors 3152 may be coupled to a common conductor (such as 2007 in FIG. 20). In embodiments, the circuit 3100 may control a column of piezoelectric elements in FIGS. 20-27.

FIG. 32 shows a circuit 3200 for controlling multiple piezoelectric elements according to embodiments of the present disclosure. In embodiments, the circuit 3200 may be disposed in an ASIC chip, where the line (either column or row) of piezoelectric elements that is disposed in a transceiver substrate and the ASIC chip may be interconnected to the transceiver substrate by bumps. As depicted, the circuit 3200 may include an array of circuit elements 3240-1-3240-*n*, where each circuit element may communicate signals with the O, X, and T electrodes of the corresponding piezoelectric element.

As depicted in FIG. 32, each circuit element (e.g. 3240-1) may include a first switch (e.g. 3202-1), a second switch (e.g. 3204-1), a third switch (e.g. 3206-1), a fourth switch (e.g. 3207-1), and a transmit driver (e.g. 3208-1). The output from the transmit driver (e.g. 3208-1) may be sent to an O electrode of the piezoelectric element via a conductor (e.g. 3210-1). During the transmit mode, each circuit element may receive a transmit driver (or driving) signal 3224 through a conductor 3222. Each second switch (e.g. 3204-1), which may be a transistor switch and controlled by a control unit 3250, may be turned on to transmit the signal 3224 to the transmit driver (e.g. 3208-1). (The electrical connection between the control unit 3250 and other components in the circuit 3200 are not shown in FIG. 32.) The transmit driver (e.g. 3208-1) may logically decode the signal, level shift it and buffer, the output signal and send the transmit output signal to the O electrode via the conductor (e.g. 3210-1). In embodiments, during the transmit mode, the first switch (e.g. 3202-1) may be turned off.

In embodiments, the control unit 3250 may decide which piezoelectric elements need to be turned on during the transmit mode. If the control unit 3250 decides not to turn on a second piezoelectric element, the first switch (e.g. 3202-2) and the second switch (e.g. 3204-2) may be turned off, while the third switch (e.g. 3206-2) and the fourth switch (e.g. 3207-2) may be turned on so that the O and X (and T) electrodes have the same electrical potential (i.e., there is a net zero volt drive across the piezoelectric layer). In in embodiments, the third and fourth switches (e.g. 3206-2 and 3207-2) may be optional. It is understood that 3 level signaling and a transmit driver that performs that is not shown explicitly. Similarly the connections to X T conductors and switches like 3206-2, 3207-2 are shown in a simplified manner.

In embodiments, during the receive mode, the first switch (e.g. 3202-1) may be turned on so that the electrical charge developed in the O electrode may be transmitted through the conductors 3210-1 and 3220 to the amplifier 3228. Then, the amplifier 3228 may amplify the electrical charge (or sensor)

signal **3226**, where the amplified signal may be further processed to generate an image. During the receive mode, the second switch (e.g. **3204-1**), the third switch (e.g. **3206-1**), and the fourth switch (e.g. **3207-1**) may be turned off so that the received signal may not be interfered.

It is noted that the entire array of the circuit element **3240-1-3240-n** may share a common amplifier **3228**, simplifying the design of the circuit **3200**. In embodiments, the X electrodes of the piezoelectric elements may be electrically coupled to the ground or a DC bias voltage via the conductors **3212-1-3212-n**, where the conductors **3212-1-3212-n** may be electrically coupled to a common conductor **3252**. In embodiments, the T electrodes of the piezoelectric elements may be electrically coupled to the ground or a DC bias voltage via the conductors **3213-1-3213-n**, where the conductors **3213-1-3213-n** may be electrically coupled to a common conductor **3254**.

In embodiments, the circuit **3200** may be coupled to a column of piezoelectric elements (e.g. **2102-11-2102-n1**) in FIG. **21**. In embodiments, a plurality of circuits that are similar to the circuit **3200** may be coupled with the multiple columns of piezoelectric elements in the array in FIG. **21**, and the conductors **3252** may be coupled to a common conductor (such as **2106** in FIG. **20**). Similarly, in embodiments, the conductors **3254** may be coupled to a common conductor (such as **2108** in FIG. **21**). In embodiments, the circuit **3200** may control a column of piezoelectric elements in FIGS. **20-27**.

In FIGS. **22-32**, conductors are used to electrically couple an electrode to another electrode. For instance, the electrodes **2006-11-2006-m1** are electrically coupled to a conductor **2007**. In embodiments, the conductors in FIGS. **22-32** may be implemented in a variety of methods, such as metal interconnect layers deposited and patterned on the substrate on which the piezoelectric elements are disposed or on a different substrate, such as ASIC, that is connected to the substrate.

FIGS. **33** and **34** show exemplary waveforms **3300** and **3400** for driving a piezoelectric element during the transmit mode according to embodiments of the present disclosure. In general, piezoelectric material may be vulnerable to damages caused by dielectric aging, and the aging may be delayed or avoided by using unipolar drive signals. The waveforms **3300** and **3400** represent the voltage potential between O and X electrodes and/or between O and T electrodes. As depicted, the waveforms may be unipolar in nature and may be a two level step waveform **3300** (i.e., the transmit driver, such as **2812**, **2912**, **3018**, **3108**, **3208**, etc. is a unipolar transmit driver) or a multilevel (such as three level) step waveform **3400**. The actual voltage amplitude may vary typically from 1.8 V to 12.6 V. In embodiments, the multistep waveform **3400** or a waveform with more steps may reduce heating in the piezoelectric element and have advantages for use during certain imaging modes, such as Doppler or harmonic imaging.

In embodiments, the frequency of the pulses in the waveforms **3300** and **3400** may vary depending on the nature of the signal needed and may vary to contain the frequency at which membrane underlying the pMUT is responsive to. In embodiments, the waveforms may also be complex signals, such as linear or non-linear frequency modulated chirp signals, or other coded signals using the Golay codes.

In embodiments, the circuits for driving the piezoelectric elements may further be designed such that the transmit output from the underlying membrane may be symmetrical in shape. In embodiments, for each signal pulse in the

waveform **3300** (or **3400**), the rising edge of the pulse may be substantially symmetrical to the falling edge of the pulse with respect to the center of the pulse. This symmetry lowers the harmonic content of the transmit signal, specially the second harmonic and other even order harmonics signal. In embodiments, the signal pulse in the waveform **3300** (or **3400**) may be a pulse width modulated (PWM) signal.

FIG. **35** shows a transmit drive signal waveform according to embodiments of the present disclosure. As depicted, the signal **3500** from the transmit driver may be symmetric and bipolar i.e., the magnitude (H1) and width (W1) of the peak maximum voltage are the same as the magnitude (H2) and width (W2) of the peak minimum voltage. Also, the slope of the rising edge **3502** is the same as the slope of the falling edge **3504**. In addition, the rising time W3 is the same as the fall time W4, where the fall time W4 refers to the time interval between the starting point of the fall and the reference voltage. Furthermore, the rising edge **3506** has the same slope as the rising edge **3502**.

During the transmit operation, the transmit drive, e.g. **3018** in FIG. **30**, may be driven by an electrical waveform, such as shown in FIGS. **33-34**. FIG. **36** shows output signals of various circuits in an imaging assembly according to embodiments of the present disclosure. In embodiments, the waveform **3602** may be an output signal from the transmit driver, e.g. **3018** and transmitted to a piezoelectric element, e.g. **3000**. In embodiments, as the piezoelectric element may have an inherent bandwidth, it may output a sinusoidal output **3604** at its resonant frequency. If the output of the transmit driver connected to the O electrode of the piezoelectric element rises very slowly, it may not be able to charge the electrode to the desired final value and thus may cause low output signals, as shown in waveform **3606**, where final amplitude is smaller than in **3602**. On the other hand, if the output signal of the transmit driver settles very quickly, the output signal of the transmit driver has larger bandwidth than the bandwidth limit of the piezoelectric element and therefore extra energy may be dissipated in heat. Therefore, in embodiments, as shown in the waveform **3608**, the piezoelectric element may be charged at a rate such that it is completely charged but not very quickly. In embodiments, the waveform **3608**, which represents the voltage potential across the top and bottom electrodes as a function of time, is closer in shape to the output of the transducer and because difference in shape is smaller, the input signal bandwidth and output signal bandwidth matches better, less loss of energy in heat occurs. In embodiments, drive impedance of transmit driver is optimized to reduce the loss of energy. Stated differently, the impedance of the transmit driver is designed to drive the piezoelectric element optimally with respect to heat dissipation and time constants needed for adequate voltage settling within a target time period.

In embodiments, the imager **120** may use a harmonic imaging technique, where the harmonic imaging refers to transmitting pressure waves on the fundamental frequency of the membrane and receiving reflected pressure waves at second or higher harmonic frequencies of the membrane. In general, the images based on the reflected waves at the second or higher harmonic frequencies have higher quality than the images based on the reflected waves at the fundamental frequency. The symmetry in the transmit waveform may suppress the second or higher harmonic components of the transmit waves, and as such, the interference of these components with the second or higher harmonic waves in the reflected waves may be reduced, enhancing the image quality of the harmonic imaging technique. In embodiments,

to reduce the second or higher harmonic waves in the transmit waves, the waveform **3300** may have 50% duty cycle.

In FIGS. **20-29**, the arrays may include multiple line units, where each line unit includes a plurality of piezoelectric elements that are electrically coupled to each other. In 5 embodiments, the line units may be driven with multiple pulses that have phase differences (or equivalently delays). By adjusting the phases, the resultant pressure waves may be steered at an angle, which is referred to as beamforming.

FIG. **37A** shows a plot of the amplitude of a transmit pressure wave as a function of spatial location along the azimuth axis of the transducer according to embodiments of the present disclosure. If the piezoelectric elements in the array are arranged in 2 dimensions and the piezoelectric 10 elements on a column in the Y direction are connected and have many columns along the X direction, the X direction is known as the azimuth direction and the Y direction is known as the elevation direction. As depicted in FIG. **37A**, the transmit pressure wave includes the main lobe and multiple side lobes. The main lobe may be used to scan tissue targets and have high pressure amplitude. The side lobes have lower amplitude but degrade quality of images and therefore it is desirable to reduce their amplitude.

FIG. **37B** shows various types of windows for apodization process according to embodiments of the present disclosure. In FIG. **37B**, x-axis represents position of a piezoelectric elements relative to the piezoelectric element at the center of an active window and y-axis represents the amplitude (or, weight applied to the piezoelectric element). As depicted, for the rectangular window **3720**, there is no weighting provided for any of the transmit lines, i.e., they are all at a uniform amplitude (i.e. symbolically 1). On the other hand, if the weighting function is implemented, as depicted by the Hamming window **3722**, lines at the center get a greater 15 weighting than ones at the edges. For instance, to apply the Hamming window **3722** to the transducer tile **210** in FIG. **3B**, the piezoelectric elements in the leftmost column (which is denoted as $-N$ in FIG. **37B**) and the piezoelectric elements in the rightmost column (which is denoted as N in FIG. **37B**) 20 may have the lowest weight, while the piezoelectric elements in the middle column may have the highest weight. This process is known as apodization. In embodiments, various types of window weighting may be applied, even though the Hamming window **3722** shown is only meant to be one example. In embodiments, apodization may be implemented by a variety of means such as scaling the transmit driver output drive level differently for different lines by employing a digital to analog converter (DAC) or by 25 keeping the same drive level but reducing the number of pixels on a line. The net effect is the side lobe level can be reduced by use of apodization, where the weighting of the transmit drive varies based on where a particular line is located within the transmit aperture energized.

In embodiments, the reduction in the voltage of the pulses or waveforms may lower the temperature at the transducer surface. Alternately, for a given maximum acceptable transducer surface temperature, transducers operating at lower voltages may deliver better probe performance, resulting in better quality images. For example, for a probe with 192 30 piezoelectric elements to reduce power consumption, transmit pressure waves may be generated by using only a portion of probe (i.e., a subset of the piezoelectric elements) and scanning the remaining elements sequentially in time using a multiplexer. Therefore, at any point of time, in the conventional systems, only a portion of the transducer elements 35 may be used to limit the temperature rise. In contrast, in

embodiments, the lower voltage probe may allow more piezoelectric elements to be addressed simultaneously, which may enable increased frame rates of the images and enhanced image quality. Significant power is also consumed 5 in the receive path where the received signal is amplified using LNAs. An imaging system typically uses a number of receive channels, with an amplifier per receiver channel. In embodiments, using temperature data, a number of receiver channels can be turned off to save power and reduce 10 temperature.

In embodiments, the apodization may be achieved by varying the number of piezoelectric elements in each line unit according to a window function. In embodiments, such a window approximation may be achieved by electronically 15 controlling the number of piezoelectric elements on a line or by hardwiring the transducer array with the required number of elements.

In general, the heat developed by a probe may be a function of the pulse duration in the transmit pulse/waveform. In general, to make the pressure waves penetrate deep in the target with better signal to noise ratio (SNR), a piezoelectric element may require long pulse trains. However, this also degrades axial resolution and also generates more heat in the piezoelectric elements. So, in the conventional systems, the number of pulses emitted is small, sometimes one or two. Since longer pulses may create more heat energy, making it impractical for their use in the conventional systems. In contrast, in embodiments, the pulses and waveforms **3300** and **3400** may have significantly 20 lower peak values, which may enable the use of long pulse trains, chirps or other coded signaling. In embodiments, the longer pulse trains do not degrade axial resolution since in the receiver matched filtering is performed to compress the waveform to restore resolution. This technique allows a better signal to noise ratio and allows signal to penetrate deeper into the body and allows for high quality imaging of targets deeper in the body.

In embodiments, a layer of Polydimethylsiloxane (PDMS) or other impedance matching material may be spun over the transducer elements in FIGS. **4-19**. This layer may improve the impedance matching between the transducer elements and the human body so that the reflection or loss of pressure waves at the interface between the transducer elements and the human body may be reduced.

In FIGS. **20-29**, more than one line unit may be created by connecting pixels in the y-direction (or x-direction), where one line unit (or equivalently line element) refers to multiple piezoelectric elements that are electrically connected to each other. In embodiments, one or more line units may also be 30 created by connecting piezoelectric elements along the x-direction. In embodiments, the piezoelectric elements in a line unit may be hardwired.

As discussed in conjunction with FIG. **18A**, each piezoelectric element **1806** may be electrically coupled to a circuit **1842**, i.e., the number of piezoelectric elements in the transceiver substrate **1802** is the same as the number of circuit **1842** in the ASIC chip **1804**. In such a case, the electrical connections of piezoelectric elements in each column (or row) may be performed electronically, i.e., the hardwire conductors (e.g. **2007**) for connecting electrodes in a column (or row) is replaced by electronic switches. Stated differently, the piezoelectric elements in a line imager/unit may be electronically connected to each other. For an electronically controlled line imager, a line imager/unit may be built by connecting each piezoelectric element of a two dimensional matrix array to a corresponding control circuit 35 (such as **1842**) of a two dimensional array of control circuits,

where the control circuits are located spatially close to pixels. To create a line element, a multiplicity of drivers controlling a column (or row) of pixels may be turned on electronically. In embodiments, the number of drivers in each line imager/unit can be electrically modified under program control and electronically adjustable, i.e., the line imager having the piezoelectric elements are electrically configurable.

In embodiments, smaller capacitance of each pixel may be driven efficiently by the distributed drive circuitry without other equalizing elements in between driver and pixel, eliminating the difficulty of driving a very large line capacitance. In embodiments, driver optimization may allow symmetry in rising edge and falling edges, allowing better linearity in transmit output, enabling harmonic imaging. (The symmetry is described in conjunction with FIGS. 33 and 34.) In embodiments, electronic control may allow programmable aperture size, transmit apodization, and horizontal or vertical steering control, all of which may improve image quality. In embodiments, the configurable line imager/unit under electronic control may be electrically modified under program control. For example, if a smaller number of connected elements is desired in the y-direction, the number may be adjusted by software control and without having to re-spin the control electronic circuitry or the piezoelectric array.

In embodiments, each line unit may be designed to consist of several sub units with separate control for each sub unit. The advantage of these sub units is that it may alleviate the difficulty of driving a large capacitive load for a line unit using one single external transmit driver. For example, if two line units are created in the place of one line unit that includes the entire piezoelectric elements in a column, two different transmit drivers (such as 2816) may be employed and each transmit driver may control half of the load of the full line unit. Also, even if one driver is used, driving the first half of the line unit and the second half of the line unit separately may improve the drive situation due to lower resistance connection to both ends of the line unit.

In embodiments, both the length and orientation of the line units may be controlled. For instance, in FIGS. 20-29, the line units may be arranged in both x and y directions. By way of example, in FIG. 30, the O electrodes along a column (e.g. 2003-11-2003-n1) may be electrically coupled to form one line unit, and the O electrodes in the other columns may be electrically coupled to form n number of line units that extend along the x-direction. More specifically, the line units that extend along the x-direction include n number of O electrodes (2003-12-2003-1n), . . . , (2003-n2-2003-nm). In embodiments, the arrangement of line units along orthogonal directions may be possible by controlling the electrical circuits in ASIC chip.

In FIGS. 20-30, each piezoelectric element may include two or more top (X and T) electrodes. In embodiments, the piezoelectric layer under these top electrode may be poled in the same direction or opposite directions. The multiple poling direction when combined with an appropriate applied signal electric field may create improvements in transducer transmit and receive sensitivities and also create additional resonances to enable wider bandwidth.

In FIGS. 20-30, each array may have one or more membranes disposed under the piezoelectric elements. In embodiments, the membranes may have multiple modes of vibration. In embodiments, one membrane may vibrate in the fundamental mode at a certain frequency while another membrane may vibrate at a different frequency determined by membrane design and relative arrangements of electrodes

with different poling directions. In embodiments, multiple membranes may be driven by same electrode set and each membrane may have different fundamental frequencies. In embodiments, each membrane may be responsive to a wide range of frequencies, increasing its bandwidth. Also, such a transducer with different poling directions may help increase transmit and receive sensitivities while also enabling a high bandwidth transducer.

In FIGS. 22, 24, 25, the X (or T) electrodes in a column may be electrically coupled to a conductor. In embodiments, these conductors may be electrically coupled to one common conductor. For instance, in FIG. 22, the conductors 2008-1-2208-n may be electrically coupled to one common conductor line so that all of the T electrodes in the array 2200 may be connected to the ground or a common DC bias voltage.

In FIGS. 20-29, each array may include piezoelectric elements that are arranged in a two dimensional array, where the number of elements in the x-direction may be the same as the number of elements in the y-direction. However, it should be apparent to those of ordinary skill in the art that the number of elements in the x-direction may be different from the number of elements in the y-direction.

In embodiments, the ASIC chip (such as 1804) coupled to the transducer substrate (such as 1802) may contain temperature sensors that measure the surface temperatures of the imaging device 120 facing the human body during operation. In embodiments, the maximum allowable temperature may be regulated, and this regulation may limit the functionality of the imaging device since the temperatures should not rise beyond the allowable upper limit. In embodiments, this temperature information may be used to improve image quality. For example, if temperature is below the maximum allowed limit, additional power may be consumed in the amplifiers to lower its noise and improve system signal-to-noise ratio (SNR) for improved quality images.

In embodiments, the power consumed by the imaging device 120 increases as the number of line units that are driven simultaneously increases. All line units in the imaging device 120 may need to be driven to complete transmitting pressure waves from the whole aperture. If only a few line units are driven to transmit pressure waves, wait and receive the reflected echo at a time, it will take more time to complete one cycle of driving the entire line units for the whole aperture, reducing the rate at which images can be taken per second (frame rate). In order to improve this rate, more line units need to be driven at a time. In embodiments, the information of the temperature may allow the imaging device 120 to drive more lines to improve the frame rate.

In FIGS. 20-30, each piezoelectric element may have one bottom electrode (O) and one or more top electrodes (X and T) and have more than one resonance frequency. For instance, each piezoelectric element 2502 in FIG. 25 may have one bottom electrode (O) and two top electrodes, where the first top electrode and the bottom electrode (O) may be responsive to a first frequency f1, while the second top electrode and the bottom electrode (O) may be responsive to a second frequency f2 that may be different from f1.

In embodiments, the electrical charge developed during the receive mode is transferred to an amplifier, such as 1811, 2810, 2814, 2910, 2914, 3010, 3016, 3128, and 3228. Then, the amplified signal may be further processed by various electrical components. As such, it should be apparent to those of ordinary skill in the art that the each of the amplifiers 1811, 2810, 2814, 2910, 2914, 3010, 3016, 3128, and 3228 collectively refers to one or more electrical components/circuits that process the electrical charge signal, i.e.,

each amplifier symbolically represents one or more electrical components/circuits for processing the electrical charge signal.

FIG. 38 shows a schematic diagram of an imaging assembly 3800 according to embodiments of the present disclosure. As depicted, the imaging assembly 3800 may include: a transceiver substrate 3801 having piezoelectric elements (not shown in FIG. 38); an ASIC chip 3802 electrically coupled to the transceiver substrate 3801; a receiver multiplexer 3820 electrically coupled to the ASIC chip 3802; a receiver analogue-front-end (AFE) 3830; a transmitter multiplexer 3824 electrically coupled to the ASIC chip 3802; and a transmit beamformer 3834 electrically coupled to the second multiplexer 3824. In embodiments, the ASIC chip 3802 may include multiple circuits 3804 that are connected to and configured to drive multiple piezoelectric elements in the transceiver substrate 3801. In embodiments, each circuit 3804 may include a receiver amplifier (or shortly amplifier) 3806, such as LNA, and a transmit driver 3808 for transmitting a signal to a piezoelectric element, and a switch 3810 that toggles between the amplifier 3806 and the transmit driver 3808. The amplifiers may have programmable gain and means to connect them to piezo elements that need to be sensed. The transmit drivers have means to optimize their impedance and means to be connected to piezoelectric elements that are to be driven.

In embodiments, the receiver multiplexer 3820 may include multiple switches 3822 and the receiver AFE 3830 may include multiple amplifiers 3832. In embodiments, each of the switches 3822 may electrically connect/disconnect a circuit 3804 to/from an amplifier 3832. In embodiments, the transmitter multiplexer 3824 may include multiple switches 3826 and the transmit beamformer 3834 may include multiple transmit driver 3836 and other circuitry not shown to control the relative delay between transmit driver waveform of the various drivers, and other circuitry not shown to control the frequency and the number of pulses for each of the transmit drivers. In embodiments, each of the switches 3826 turn on during a transmit operation and connect to circuit 3804, while switches 3822 turn off, while switch 3810 connects to transmit driver 3808. Similarly, during a receive operation, switches 3826 turn off while switches 3822 turn on, while switch 3810 is connected to amplifier 3806.

In embodiments, the switches 3810 may be toggled to the transmit drivers 3808 during the transmit mode and toggle to the amplifiers 3806 during the receive mode. In embodiments, a portion of the switches 3822 may be closed so that the corresponding circuits 3804 may be set to the receive mode. Similarly, a portion of the switches 3826 may be closed so that the corresponding circuits 3804 may be set to the transmit mode. Since a portion of the switches 3822 and a portion of the switches 3826 may be closed simultaneously, the imager assembly may be operated in both transmit and receive modes simultaneously. Also, the receiver multiplexer 3820 and the transmitter multiplexer 3824 reduce the number of ASIC pins. In embodiments, the receiver multiplexer 3820, receiver AFE 3830, transmitter multiplexer 3824, and transmitter beamformer 3834 may be included in the circuits 215 in FIG. 2.

In embodiments, each piezoelectric may have more than two electrodes, where one electrode may be in the transmit mode to generate pressure waves while the other electrode may be simultaneously in the receive mode to develop electrical charge. This simultaneous operation of transmit and receive modes may allow three dimensional imaging.

While the invention is susceptible to various modifications and alternative forms, specific examples thereof have been shown in the drawings and are herein described in detail. It should be understood, however, that the invention is not to be limited to the particular forms disclosed, but to the contrary, the invention is to cover all modifications, equivalents, and alternatives falling within the scope of the appended claims.

What is claimed is:

1. A transceiver, comprising:
 - a substrate;
 - a membrane suspending from the substrate;
 - a bottom electrode disposed on the membrane;
 - a piezoelectric layer disposed on the bottom electrode;
 - first and second top electrodes disposed on the piezoelectric layer, the first top electrode being electrically separated from the second top electrode, wherein the first top electrode is responsive to at least a first frequency and the second top electrode is responsive to at least a second frequency different from the first frequency; and
 the piezoelectric layer including a first portion located under the first top electrode and poled in a first direction and a second portion located under the second top electrode and poled in a second direction that is opposite to the first direction.
2. The transceiver of claim 1, further comprising:
 - a first conductor configured to couple the first top electrode to a ground or a DC bias voltage; and
 - a second conductor configured to couple the second top electrode to a ground or a DC bias voltage.
3. The transceiver of claim 1, further comprising a third top electrode disposed on the piezoelectric layer and spatially separated from the first and second top electrodes.
4. The transceiver of claim 3, wherein the piezoelectric layer includes a third portion under the third top electrode and the third portion is poled in one of the first and second directions.
5. An imaging device, comprising:
 - a transceiver substrate including:
 - a substrate;
 - at least one membrane disposed on the substrate; and
 - a plurality of piezoelectric elements disposed on the at least one membrane, each of the plurality of piezoelectric elements including:
 - a bottom electrode;
 - a piezoelectric layer disposed on the bottom electrode;
 - first and second top electrodes disposed on the piezoelectric layer, the first top electrode being electrically and spatially separated from the second top electrode, wherein the first top electrode is responsive to at least a first frequency and the second top electrode is responsive to at least a second frequency different from the first frequency; and
 - the piezoelectric layer including a first portion located under the first top electrode and poled in a first direction and a second portion located under the second top electrode and poled in a second direction that is opposite to the first direction; and
 - an Application-Specific Integrated Circuit (ASIC) chip electrically coupled to the transceiver substrate by a three dimensional interconnection mechanism and including:
 - at least one circuit for controlling one or more of the plurality of piezoelectric elements; and

a control unit electrically coupled to the at least one circuit and controlling the at least one circuit.

6. The imaging device of claim 5, wherein the bottom electrode is a signal electrode and wherein each of the first and second top electrodes is a common electrode and connected to one of a ground and a DC bias.

7. The imaging device of claim 5, wherein the at least one circuit includes:

a transmit driver for sending a transmit signal to the bottom electrode; and

an amplifier for receiving a receive signal from the bottom electrode and amplifying the receive signal.

8. The imaging device of claim 7, wherein the at least one circuit includes:

a switch having a first terminal electrically coupled to the bottom electrode and a second terminal toggling between two conductors that are coupled to the transmit driver and the amplifier.

9. The imaging device of claim 8, wherein the second terminal of the switch toggles to the conductor coupled to the amplifier during a receive mode so that an electrical charge developed on the bottom electrode is transferred to the amplifier.

10. The imaging device of claim 7, wherein the transmit signal has rising and falling edges and the rising and falling edges are symmetrical to each other and high and low portions of transmit signal are substantially equal.

11. The imaging device of claim 7, wherein the transmit signal is a pulse wave modulated (PWM) signal.

12. The imaging device of claim 11, wherein a width of the PWM signal is adjusted to implement a transmit apodization.

13. The imaging device of claim 10, wherein the transmit signal has two or more levels and a number of the levels is used to encode weighting for the apodization.

14. The imaging device of claim 5, wherein each of the plurality of piezoelectric elements further includes three conductors that are coupled to the bottom electrode, first top electrode and second top electrode, respectively, and the three conductors are electrically connected to the at least one circuit by the three dimensional interconnection mechanism.

15. The imaging device of claim 5, wherein the three dimensional interconnection mechanism includes at least one of Cu pillars and solder bumps.

16. The imaging device of claim 5, wherein each of the plurality of piezoelectric elements further includes a third top electrode disposed on the piezoelectric layer and spatially separated from the first and second top electrodes.

17. The imaging device of claim 5, further comprising: at least one temperature sensor for measuring temperature of the imaging device.

18. The imaging device of claim 17, wherein the ASIC chip includes a low-noise-amplifier (LNA) and receives temperature data from the at least one temperature sensor and, using the temperature data, adjusts at least one of an imaging frame rate and a signal-to-noise ratio of the LNA.

19. The imaging device of claim 18, wherein using temperature data, a number of receive channels, with a LNA per channel, are turned off to reduce temperature.

20. The imaging device of claim 5, further comprising: a layer disposed on the plurality of piezoelectric elements and configured to reduce impedance mismatch at an interface between the piezoelectric elements and a target to be imaged.

21. The imaging device of claim 5, wherein the plurality of piezoelectric elements are arranged in a two dimensional array.

22. The imaging device of claim 21, wherein the two dimensional array is configured to operate in a biplane mode where a portion of piezoelectric elements in a column of the two dimensional array simultaneously generate pressure waves and a portion of piezoelectric elements in a row of the two dimensional array simultaneously develop electrical signals.

23. The imaging device of claim 5, wherein the at least one membrane is formed by etching a cavity in the substrate.

24. The imaging device of claim 5, wherein the at least one circuit controls a power delivered to a piezoelectric element to thereby control a penetration depth of a pressure wave generated by the piezoelectric element.

25. The imaging device of claim 5, further comprising: at least one port for receiving one end of a cable that is configured to communicate with an external device; a Field Programmable Gate Array (FPGA); and a communication unit, for communicating with an external device through the cable.

26. The imaging device of claim 25, wherein the external device is one of a smart phone and a tablet.

27. The imaging device of claim 25, further comprising: at least one port of a type selected from the group consisting of Universal Serial Bus (USB)2, USB3, and USB 3.1 and USB-C.

28. The imaging device of claim 25, further comprising: a communication unit for wirelessly communicating a signal with an external device, wherein the cable is used to transfer power from a display unit.

29. The imaging device of claim 5, further comprising a battery.

30. The imaging device of claim 5, further comprising: a housing for enclosing the imaging device; and a mechanism for dissipating heat energy generated to reduce temperature of the transceiver substrate and the housing.

31. The imaging device of claim 5, wherein to reduce temperature rise in the transceiver substrate and a body of a first enclosure encasing the imaging device, a second enclosure accommodates some circuitry originally inside the first enclosure, wherein the two enclosures are connected using a cable.

32. The imaging device of claim 31, wherein the some circuitry includes a FPGA.

33. The imaging device of claim 5, wherein the imaging device communicates with an external device for display and control using USB3 protocol.